Applied Computer Science 2026, vol. 22, no. 1, pp. 154–170
https://doi.org/10.35784/acs_8050

Submitted: 2025-07-05 | Revised: 2025-08-18 | Accepted: 2025-09-15


*Keywords: optimization, metaheuristic algorithms, mobile robot path planning, path planning*

*Sheren SADIQ* [1], *Araz ABRAHIM* [1], *Haval SADEEQ* [1*]
[1] Duhok Polytechnic University, Iraq, sheren.hasan@dpu.edu.krd, araz.abrahim@dpu.edu.krd, haval.tariq@dpu.edu.krd
[*] Corresponding author: haval.tariq@dpu.edu.krd

# A comprehensive review of metaheuristic algorithms for mobile robot path planning

**Abstract**

*Path planning and optimization are essential topics in robotics because they directly affect the effectiveness and safety of robot navigation. The application of metaheuristic methods and algorithms in the field of robot motion planning has attracted the attention of researchers in the field of robotics, given the ease of use and efficiency of the methods in coordinating agents. Metaheuristic algorithms have attracted much attention in recent years due to their efficiency in solving complex optimization problems. This paper summarizes the mobile robot path planning with metaheuristic algorithms, along with their strengths and weaknesses. In this paper, we will focus on a few meta-algorithms: Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Artificial Fish Swarm Algorithm (AFSA), Grey Wolf Optimizer (GWO), Bat Algorithm (BA), Firefly Algorithm (FA), and Cuckoo Algorithm (CA). In addition, this study reviews the status of path planning research and its major difficulties to be solved, along with the future trends of path planning.*

## 1. INTRODUCTION

One of the key challenges for an autonomous robot is path planning (Liu et al., 2023). Since the environment is full of obstacles, finding a collision-free motion to move a robot from its starting position to its goal is critical. In general, a robot can take a different number of possible paths from its starting point to its goal (Hewawasam et al., 2022; Sánchez-Ibáñez et al., 2021). However, in most cases, the best possible path is chosen based on some criteria, such as the lowest energy consumption, the shortest distance, the smoothest path, etc., in the least amount of time (Kamil et al., 2025). Mobile robotics research has been an emerging field for the last three decades. The main focus of current mobile robotics research is on path planning algorithms and optimization in both static and dynamic environments (El-Kenawy et al., 2022). Mobile robot path planning is a challenging optimization problem that requires careful modeling of the environment, definition of objectives, selection of appropriate algorithms, and efficient evaluation of candidate solutions. Metaheuristic methods, such as evolutionary algorithms, have shown promise in finding high-quality solutions to this problem (Promkaew et al., 2024).

Optimization is essential in many domains such as business, engineering, and industrial design (Zidani et al., 2024). Optimization goals vary widely, ranging from maximizing efficiency and performance to minimizing cost and energy consumption. It is no exaggeration to say that optimization is needed for everything from Internet routing to vacation planning, from engineering design to business planning. In practice, time, money, and resources are always limited, so we must figure out how to use these precious resources as efficiently as possible while dealing with a variety of different constraints. Mathematical programming, or optimization, refers to the use of mathematical techniques to study these planning and design problems. Most real-world applications are often quite nonlinear, requiring advanced optimization techniques to solve them. Computer simulations are becoming an important tool for applying various effective search strategies to solve such optimization challenges. Behind any computational technique or computer simulation, there are always certain algorithms at work. The efficiency and performance of an algorithm is determined by its basic elements and the way they interact (Y. Xu et al., 2023; L. Yang et al., 2023).

There are many techniques for classifying optimization algorithms. Examining the nature of the algorithm, which divides algorithms into two groups-deterministic algorithms and stochastic algorithms-is a straightforward method. Deterministic algorithms have a strict process with recurring paths and values for both design variables and functions. For example, a deterministic algorithm such as hill climbing will always follow the same path for the same starting point whether it is run now or tomorrow. Stochastic algorithms, on the other hand, are inherently unpredictable. For example, genetic algorithms work well. Every time the program is started, the strings or solutions in the population will change because the algorithms use certain pseudorandom numbers (X.-S. Yang, 2020). The individual paths are not perfectly repeatable, but the final results may not be significantly different. A third category of algorithms is a mixture or combination of stochastic and deterministic algorithms. An excellent example is hill climbing with unpredictable restarts. The general idea is to use a deterministic method with variable starting points. Compared to a simple hill-climbing method, which might get stuck on a nearby peak, this strategy offers certain advantages. In the optimization literature, this hybrid algorithm is categorized as a type of stochastic algorithm because it has a random element.

Although the path planning problem dates back to the 1960s, the interest in path planning for mobile robots increased after the work of the authors in (Montiel et al., 2015), after which many methods were published. The two main categories of current approaches are heuristic and classical path planning (Saeed et al., 2020). Cell decomposition, the potential field method, subgoal networks, and roadmaps are examples of traditional techniques. Finding a path from an initial position to a goal position involves following a set of predetermined steps. In classical approaches, only deterministic activities are considered (Abdulsaheb et al., 2023). However, classical approaches have been found to have several drawbacks, including high temporal complexity in high dimensions, trapping in local minima, and high computational cost (Wahab et al., 2020a). Due to the shortcomings of conventional search methods, metaheuristic approaches have attracted much interest in the research field of path planning for mobile robots, which makes it difficult to obtain precise answers. Many heuristic methods and techniques have been proposed, such as Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithm (GA). However, since metaheuristic methods are stochastic, they naturally produce near-optimal rather than exact solutions; increasing interest does not reduce the accuracy of the answers. Recent research Promkaew et al. (2024) has found that these algorithms prioritize computational feasibility and efficiency over guaranteed accuracy, making it difficult to obtain accurate answers in a highly complex and dynamic environment.

Previous surveys have addressed mobile robot path planning, such as Wahab et al. (2020a), which compared classical and metaheuristic methods, and Yang et al. (2023), which provided a broad overview including classical, heuristic, and learning-based approaches. In contrast to these surveys, this article focuses exclusively on recent metaheuristic advances (2020-2025), highlighting hybridization trends, quantitative performance comparisons, and practical guidance, thus filling a gap not covered in previous works.

This paper provides an extensive and comprehensive review of recent applications and the current state of research on different types of metaheuristics used to efficiently solve the problem of mobile robot path planning in known, static, and structured environments. This review includes nearly 22 relevant articles on research in this area, mainly published in the last three years. These papers mostly fall into the categories of swarm intelligence algorithms, evolutionary algorithms, and hybrid algorithms. While these categories of metaheuristics have been used either independently or collaboratively, or as components of other algorithms, the latter hybridization has utilized increasingly diverse metaheuristics, demonstrating a growing trend toward algorithmic hybridization. This hybridization necessarily involves enhancements of existing metaheuristics along with the incorporation of new search strategies and heuristic methods for more effective and efficient solutions. These trends substantiate the use of metaheuristics and their properties in synergy with each other for the most effective solution of the subject optimization problem.

Here are some contributions of this article.

- Provide a clear definition of metaheuristic algorithms and discuss their importance in the field of optimization, with a particular focus on path planning for mobile robots.
- Introduce the concept of path planning, its challenges, and its applications in various domains such as agriculture, warehouse automation, and autonomous vehicles.
- Review previous studies that have compared different metaheuristic approaches in path planning scenarios, highlighting key findings and results.
- Discuss the emergence of hybrid algorithms that combine the strengths of two or more metaheuristic algorithms for improved performance.
- Identify common challenges associated with metaheuristic algorithms in path planning, such as high computational cost, convergence issues, and scalability.

– Conclude with a summary of key findings from the literature review, highlighting the value of metaheuristic algorithms in improving mobile robot path planning.

## 2. MOBILE ROBOT PROBLEM

A key component of mobile robotics is navigation, which involves accurately locating the robot, determining its path, and following it. The navigation challenge can be divided into three sub-problems, as shown in Figure 1: (1) localization - identifying the robot's current position relative to its environment; (2) path planning - determining an efficient route from the starting point to the destination; and (3) object recognition or mapping - identifying the target point and interpreting the environment (Abed et al., 2021).

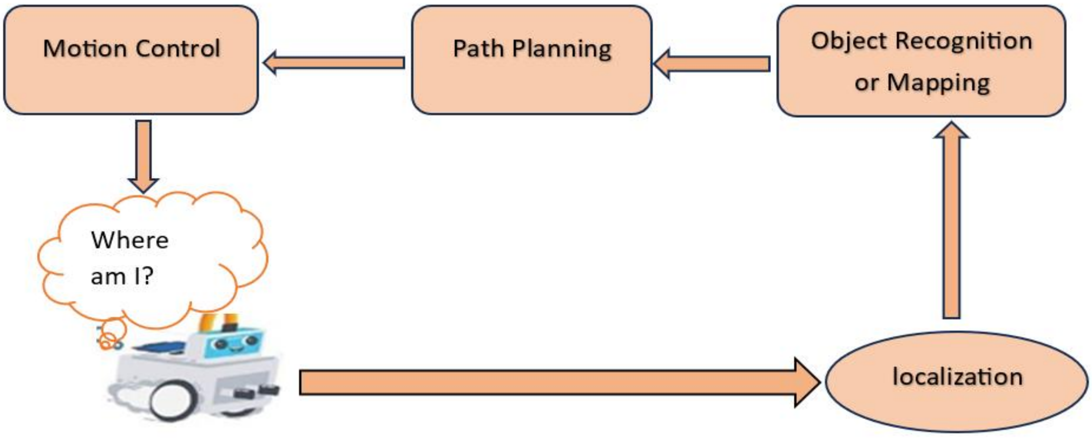


**Fig. 1. Mobile robot problem**

Localization: the robot must determine where it is in relation to its environment; mapping or recognition: A map of the robot's environment is needed to determine its current location. The robot understands locations and routes by using the map, and path planning: determining a path for the mobile robot in which the robot must use an efficient robot adjustment technique to identify the desired direction in advance, and motion control: In order to travel the intended path, the robot must vary its motor power (Abed et al., 2021).

Robot environments can be divided into two categories: dynamic environments and static environments. In general, obstacles in a dynamic environment can be both moving and stationary, while obstacles in a static environment are only stationary. Furthermore, the environment can be classified as known or unknown based on the amount of knowledge available. The term "obstacle avoidance" is typically used when referring to an unidentified environment, meaning that robots navigate freely in this area without encountering any obstacles. When designing the path of a mobile robot, several issues must be considered, as shown in Figure 2.

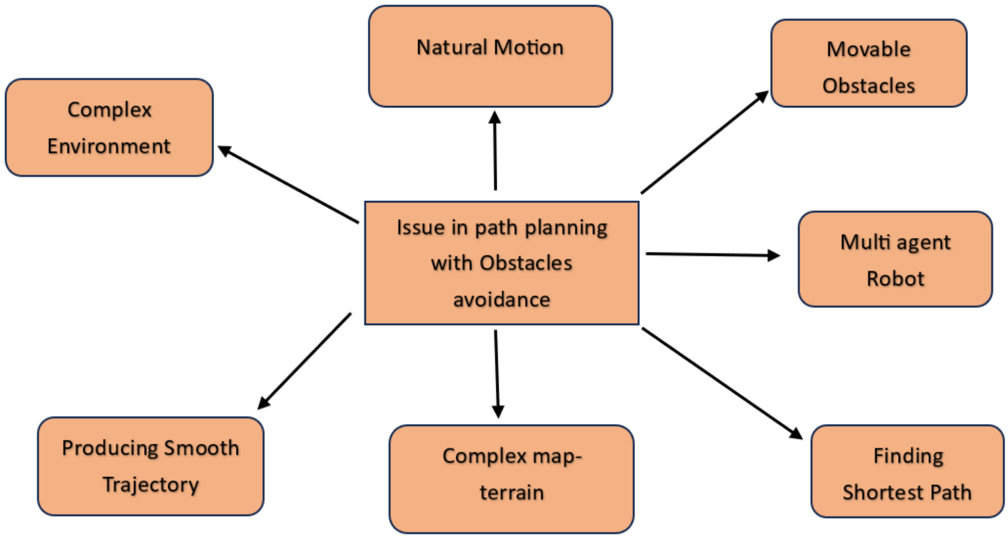


**Fig. 2. Issues in path planning**

## 3. META-HEURISTIC METHODS

One type of optimization algorithm is the metaheuristic approach, which uses iterative processes to find near-optimal solutions to complex problems (H T Sadeeq et al., 2023). These methods are designed to be more efficient and effective than traditional exact optimization methods (Sadeeq & Abdulazeez, 2022; Haval Tariq Sadeeq et al., 2025); therefore, they can be computationally expensive and impractical for large-scale tasks (Yahia et al., 2023). For mobile robots, path planning is the determination of a feasible route that will take them from one location to another while avoiding obstacles and maximizing a number of factors, including safety, smoothness, and distance. Because metaheuristic algorithms can effectively traverse complicated search spaces, they have been used extensively to solve this problem.

Heuristic-based approaches have several advantages, one of which is their ability to provide acceptable convergence (Haval Tariq Sadeeq et al., 2023), which is very useful for solving NP-complete problems (Nondeterministic Polynomial Time and NP-hard), which means finding efficient solutions to complex problems (Rafai et al., 2022; Haval T Sadeeq, 2025). There are local and global branches of the path planning problem (Liu et al., 2023). The local path planning problem determines the path when the mobile robot's mobility causes its environment to change constantly. In contrast, the terrain (conditions and obstacles) must remain stable, and the environment is fully understood in advance in global path planning (Karur et al., 2021). Some of the most commonly used techniques include Ant Colony Optimization (ACO), Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Fish Swarm Algorithm (AFSA), and Grey Wolf Optimizer (GWO). Specifically, these algorithms were chosen because they represent the most widely cited and frequently applied techniques in mobile robot path planning. Their primary objective is to determine an optimal feasible path from a starting point to a final destination while avoiding obstacles and optimizing the distance, smoothness, and safety of the path, as shown in Figure 3. There are currently three popular classification techniques for metaheuristic algorithms: (1) by the origin of the inspiration; (2) by whether they are inspired by nature; and (3) by individual or trajectory (Abed & Jasim, 2024; Y. Xu et al., 2023).

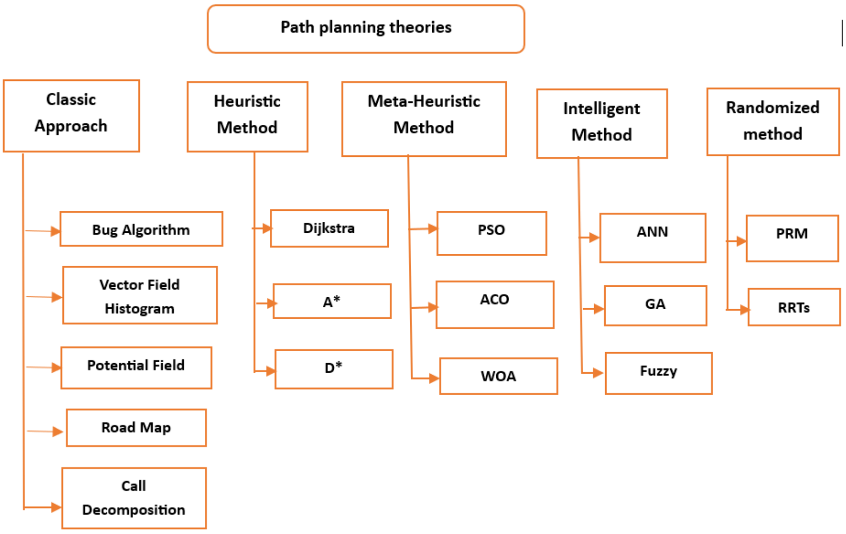


**Fig. 3. Path planning theories and techniques**

Table 1 provides a summary of the strengths and weaknesses of the algorithms based on the classification approaches and methods proposed in this study. In addition, it shows a performance comparison of different metaheuristic algorithms and methods for mobile robot path planning and optimization. It also shows the main differences between their performance, which can be useful for both researchers and practitioners to choose the best algorithm according to their applicability needs (Abdulsaheb et al., 2023).

**Tab. 1. Metaheuristic algorithms and methods for planning the paths of mobile robots**

| # | Ref. | Algorithms | Strengths | Weaknesses |
|---|---|---|---|---|
| 1 | (Awadallah et al., 2025) | -Ant Colony Optimization- (ACO) | - Effective for multi-objective optimization<br>- Good performance in complex environments | - Slower rate of convergence than other algorithms<br>- Difficulty in balancing exploration and exploitation |
| 2 | (Gad, 2022) | Particle Swarm Optimization (PSO) | - Fast convergence<br>- effective for path planning efficiency | - Possibility of getting sucked into local optima<br>- Difficulty in handling constraints |
| 3 | (Gen et al., 2023) | Genetic Algorithms (GA) | - Good performance in terms of path smoothness and safety<br>- Capable of managing complex objective functions. | - Computationally expensive<br>- Difficult to maintain population diversity |
| 4 | (Alhaqbani et al., 2022) | Artificial Fish Swarm Algorithm- (AFSA) | - Good performance in terms of path planning efficiency and smoothness | - Difficulty in handling constraints - sensitivity to parameter tuning |
| 5 | (Makhadmeh et al., 2022) | Grey Wolf Optimizer (GWO) | - Good performance in terms of path planning efficiency and smoothness | - Difficulty in handling constraints<br>- Sensitivity to parameter tuning |
| 6 | (Dao & Nguyen, 2024) | Bat Algorithm | - Adapt to dynamic environments<br>- Effectively manage multiple objectives | - Slower convergence speed compared to some other algorithms<br>- Prone to getting stuck in local optima |

To support our selection of the “most commonly used” algorithms in our review, we extracted a simple index from recent open access reviews (2020-2025) that counts the number of reviews that describe an algorithm as commonly used in path planning for mobile robots. The results show that PSO clearly leads, followed by GA and ACO, and then GWO/BA/AFSA. This result is consistent with recent qualitative reports confirming that PSO (often with GA and ACO) is the most studied and applied algorithm in the field (Ahmad et al., 2026; Teja et al., 2025). Figure 4 shows the number of reviews (2020-2025) that describe the algorithm as “popular/most used” in mobile robot path planning. The aggregated results of recent reviews show PSO (3 reviews), GA (2), ACO (2), and then GWO/BA/AFSA (1 each). This indicator is supported by recent reviews that explicitly confirm that PSO (often in combination with GA and ACO) is the most popular in the field.

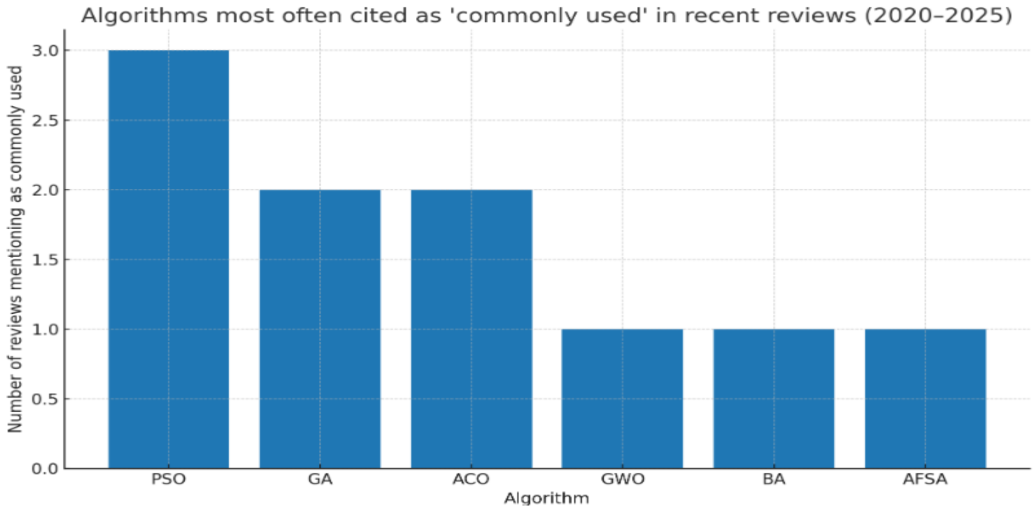


**Fig. 4. Most popular algorithms in the last 5 years**

## 4. LITERATURE REVIEW

Since path planning of mobile robots is responsible for enabling self-directed movement through terrain, it has been a focus of research in robotics. There are several solutions to the problem of finding the best, safest, and most efficient path through computation. The most popular of these are metaheuristic algorithms, which solve nonlinear and multi-objective optimization problems. Let's see what is going on in metaheuristic algorithms and how they are used for mobile robot path planning.

Gao et al. (2020) introduced the enhanced heuristic ant colony optimization EH-ACO algorithm for mobile robot path planning. In their study, they designed an improved guidance information formula that includes both the distance to the target and the obstacle positions to guide the ants along safer and more efficient paths. In addition, they proposed a parallel version of the algorithm by dividing the search space into sub-regions, which enables parallel optimization and enhances the exploration capability of the algorithm. Their experimental results showed that EH-ACO consistently outperformed traditional ACO and several state-of-the-art algorithms in terms of path length, smoothness, and computational efficiency. Specifically, EH-ACO achieved an average path length 12.5% shorter than traditional ACO and 8.7% shorter than other algorithms, proving its effectiveness in both static and dynamic environments.

Ajeil et al. (2020) introduced for the first time a novel solution to the path planning problem in autonomous mobile robots in both static and dynamic environments using the hybrid practical swarm optimization-modified Firefly PSO-MFB algorithm. Their method incorporates a grid model of the environment, assigns a potential value to each cell, and uses the hybrid PSO-MFB algorithm to obtain an optimized initial path that minimizes distance and ensures smoothness. The hybrid algorithm was combined with a local search method to handle infeasible points and convert them into feasible solutions. An obstacle detection and avoidance module was implemented by the researchers, whereby the robot makes trajectory changes to avoid collisions. The initial path was then refined using optimization techniques to reduce both the total path length and the number of waypoints. They used cubic spline interpolation to obtain a continuous, smooth trajectory from the source to the destination. They conducted simulations in various static and dynamic environments, and the results proved that the hybrid PSO-MFB outperformed other state-of-the-art path planning methods. The optimal path obtained by using the proposed method was 14.6384 meters in length.

Authors in (Y. Li et al., 2020) proposed an improved genetic algorithm GA algorithm to improve the performance of mobile robot path planning conducted with Grey Wolf Optimizing for enhanced application. APF-GWO was used to improve the shortcomings of the standard GA regarding the problem of local optimization and early convergence. In this context, GWO was used to improve the ability of the GA to perform worldwide search. It can be seen that the GA-GWO algorithm is able to generate shorter collision-free paths with faster computation times compared to other methods.

The authors in G. Xu et al. (2020) proposed a new method based on online variable optimization for dynamic path planning of mobile robots with differential propulsion. This paper uses a bug path planner that guides the robot to move toward the goal until an obstacle is detected. It then makes further movements in the environment to continue moving towards the goal.

The authors in Panda et al. (2020) developed a crowded environment enhanced opposition-based Firefly algorithm for mobile robot path planning. The authors of this paper introduced the traditional Firefly algorithm combined with an opposition-based learning strategy. This strategy diversified the search process and improved speed convergence by considering all current solutions and their opposites. Potential paths were ranked by fitness criteria, including distance reduction and obstacle avoidance. The ability of the algorithm to explore more search space becomes critical in highly crowded environments. The method has been tested in several simulation scenarios that mimic real-world crowded environments. The results obtained show a robust handling of dynamic or crowded environments within improved opposition-based Firefly-based methods, where such methods lead to highly significant efficiencies when compared to traditional path planning; additionally, improved computational efficiency has been provided through reduced computations, which contribute to the increase in time reductions within path plans. In addition, the authors in (Mohanty, 2020) focused on the intelligent cuckoo search algorithm. The proposed methodology will include mechanisms for handling uncertainties, including dynamic obstacles and environmental changes, to allow a robot to change its course in real time.

(Wahab et al., 2020b) presented an optimization method on the path plan of the moving target through a multi-objective technique that applies to finding a path using moving targets of the robot as it moves, based on the "bat algorithm" (BA). This work tries to optimize a few objects together by smoothing the path and avoiding collisions along the way, aiming to ensure less path length from Wahab et al. (2020a). According to the obtained experimental results, it can be manifested that the enhanced BA algorithm built optimal but shorter and smoother, as well as safer paths over other traditional algorithms in comparison. Because of this, therefore, the capabilities of the proposal have the ability to successfully deal with real dynamic obstacles to reach a final moving target.

The authors in (Singh et al., 2021) have gone a step further and proposed modifications such as the introduction of the tournament selection function and the adaptation of algorithm parameters to the conventional cuckoo search algorithm. The researchers made these modifications to improve the efficiency of the algorithm in terms of computation time and path length.

In another paper, Yuan et al. (2022) presented an improved particle swarm optimization PSO for path planning on raster maps. Their method is based on combining PSO with differential evolution DE. DE is used to generate an initial collision-free path, while PSO is used to optimize the trajectory to reduce collisions. The simulation results show that the APF-PSO approach was able to efficiently design a collision-free path with superior path length and lower computation time compared to a traditional PSO algorithm.

The authors Kumar and Sikander (2022) combined the improved Artificial Bee Colony (ABC) with Evolutionary Programming (EP) to provide optimal path planning for mobile robots. According to the improvement of ABC considered in this paper, an improved initialization method is used in addition to the adaptive control parameter to improve exploration capability and exploitation. The improved ABC had a hybridization with EP in terms of improving the convergence speed as well as the global search capability. Experimental results on different reference environments have proven that hybrid ABC-EP outperforms other modern methods, such as Genetic Algorithm (GA), Practical Swarm Optimization (PSO), and Standard ABC, on many key points: path length, safety, and smoothness. -Path length: 5.75%, search cost: 44.38%, path smoothness: 41.08%.

The authors in (F.-F. Li et al., 2022) presented a method that combines continuous segmented Bézier curves and an improved artificial fish swarm technique for path planning. By relying on Dijkstra's algorithm, which provides practical solutions and a range of step sizes, the proposed approach was able to overcome the low accuracy of the original artificial fish swarm algorithm, its many turning points, and its long planning paths. To facilitate the planned paths, Bessel curve theory was applied to ensure the continuity of the paths in direction and curvature. Simulations show that the improved artificial fish swarm technology guarantees the shortest average path under the same network environment and high planning accuracy.

The authors in Rodríguez-Molina et al. (2022) proposed a new approach based on online variable optimization for dynamic path planning of mobile robots with differential propulsion. The proposed method is based on the use of Bug0's path planner, which guides the robot towards the goal until it detects an obstacle, and then follows the surroundings of the obstacle until it can continue to reach the goal. These authors used simulations to prove the effectiveness of the proposed algorithm for a differentially driven mobile robot and showed that the results of the proposed method outperformed those of other metaheuristic methods in terms of path quality and efficiency.

The authors in Zhang et al. (2022) proposed the new hybrid method of PSO with another metaheuristic approach for optimization problems: a firefly approach (FA). The FA algorithm was used to explore the search space globally, while PSO was used to exploit the local search space to avoid local optimization. It was observed that the path length and computation time were improved using the proposed hybrid algorithm compared to standalone FA and PSO based approaches. A hybrid algorithm achieved a path length 12.5% shorter than that obtained with FA and 9.3% shorter than that obtained with PSO. It has been tested in several environments with different obstacle configurations. The results obtained ensure the ability of this algorithm to find collision-free paths for complex, diversified environments. Compared to other state-of-the-art algorithms such as Ant Colony Optimization and Improved Sine Cosine Algorithm, the proposed hybrid algorithm produced 11.4% and 8.9% shorter paths, respectively.

Authors in Abdul Khaleq et al. (2022) proposed two intelligent hybrid algorithms for path planning using two hybrid swarm intelligence optimizations, i.e., Ant Colony Optimization with a particle swarm, ACO-PSO (abbreviated as HACO-PSO to utilize the ACO for its global exploratory capability alongside PSO's local exploitative capability), and ACSA. Results showed that their results proved the new HACO-PSO is shorter by up to 15% than ACO, while about a 12% improved result for PSO over a single use is realized in using these algorithms. Similar to the efficiency improvement for short path generation, the computational time is reduced by 18% and 21% compared to ACO and PSO, respectively. HFA-PSO generated paths that were 14% shorter than FA and 10% shorter than PSO in terms of path length. Computation time is also reduced by 16% and 19% compared to FA and PSO, respectively.

The researchers in Kumar et al. (2022) proposed a novel approach to improve the path planning and control of mobile robots. The authors focused on optimizing the robot's trajectory by using a modified Cuckoo Search (CS) algorithm. The researchers Garip et al. (2022) also presented a new algorithm that combines the strengths of three optimization techniques: Particle Swarm Optimization (PSO), Firefly Algorithm (FA), and Cuckoo Search (CS).

The authors in (Abu et al., 2023) proposed an optimization approach for mobile robot path planning using an improved version of the Genetic Algorithm (GA). The main improvements were the introduction of a new crossover operator that ensures the feasibility of the generated paths, a new adaptive mutation operator that regulates the mutation rates based on the population diversity, and elitism to keep the best solutions over generations. The improved GA is combined with a Bezier curve (GA-BZ) for dynamic obstacles to generate smooth trajectories. In addition, a Voronoi diagram-based method was used to generate the initial population in the GA, which greatly improves the convergence speed.

Dai et al. (2023) proposed a whale optimization algorithm to solve path planning problems in the case of the mobile robot, with convergence improvement through the adaptation technique. In the design, virtual obstacles were set to avoid the local optimal trap. These were obtained through experimentation, and the results reflected that the value of average fitness for the novel wolf optimization algorithm (NWOA) showed a gain of about 32.0% when compared with that before the improvement. The simulation showed that the NWOA has a better dynamic planning ability with a faster convergence rate compared to the standard WOA applied in the path planning task of a mobile robot.

In the paper H. Li et al. (2023), the authors presented the improved hybrid artificial fish swarm algorithm AFSA to solve the path planning problem of the Automated Guided Vehicle AGV by using adaptive parameters, 2-opt operation, chaos theory, and differential evolution to obtain the shortest and smoothest path. The problems faced by traditional AFSA include low optimization accuracy and inability to consider local and global information. Against the above limitations and problems, the authors proposed some improvements: improving the adaptive field of view and adjusting the step size to improve both exploration and exploitation capabilities. In addition, a 2-opt operation is added to eliminate the randomness of the behavior and improve the local search. The authors have incorporated AFSA into the differential evolution algorithm and have come up with a hybrid algorithm that explores the advantages of both strategies. The proposed method mainly aims at finding the shortest path for the AGV considering obstacles among other constraints. Some simulation scenarios have been executed and compared with some other alternative path planning algorithms by the proposed Improved Hybrid Artificial Fish Swarm Algorithm IHAFSA algorithm. Experimental results show that the proposed IHAFSA algorithm outperforms the traditional AFSA algorithm and other algorithms in path length, smoothness, and computational efficiency in path planning problems for an AGV.

The authors in Zou et al. (2023) presented a fusion algorithm to solve the mobile robot path planning problem by combining the dynamic window technique and the improved mayfly optimization algorithm based on Q-learning IMOA-QL. The authors developed the IMOA-QL algorithm to overcome the disadvantages of the basic MOA algorithm (including slow convergence time, low accuracy, instability, etc.). This method improved the speed of convergence and the ability to search worldwide. This combination successfully demonstrated the dynamic real-time obstacle avoidance capabilities of the robot.

The authors in (Tian et al., 2024) proposed a hybrid firefly-whale optimization algorithm, known as FWOA, for path planning and function optimization of mobile robots. The quintessence of this proposed method is how it balances exploration and exploitation. This is due to the nature of the FWOA itself and the fact that it relies on the multi-population approach, with the research community and the fishing group. This feature allows the algorithm to improve the local search capabilities. In this work, WOA is combined with the Firefly algorithm to improve the diversity and convergence speed of the algorithm. The authors tested FWOA on 23 reference functions and challenges related to mobile robot path planning. Compared with other metaheuristic algorithms such as genetic algorithm (GA), practical swarm optimization (PSO), and standard WOA, the results show that FWOA achieves faster convergence speed and better solution accuracy.

The authors in (Abed & Jasim, 2024) have proposed a multi-objective optimization approach using the BAT algorithm for path planning of mobile robots with a moving target. In this work, it has been directed to improve several objectives simultaneously: shorter path, smoother path, and safety. The performance of the algorithm was tested by simulations in dynamic environments with moving targets. Experimental results showed that the modified BA algorithm generates shorter, smoother, and safer paths compared to other traditional algorithms. These results demonstrated the ability of the proposed approach to deal with dynamic obstacles and a moving target. It is worth noting that Table 2 presents a selection of studies on path planning, highlighting the algorithms used and providing a brief description of the corresponding results.

**Tab. 2. Literature of some studies in path planning using metaheuristic algorithms**

| # | References | Algorithm | Short description | Results and findings |
|---|---|---|---|---|
| 1 | (Gao et al., 2020) | Enhanced Heuristic ACO | This paper addresses the shortcomings of traditional ACO in mobile robot path planning, with consideration for both improved convergence speed and reduced turning points in the path. | The enhanced ACO algorithm showed faster convergence and smoother paths, outperforming conventional ACO methods in simulation tests. |
| 2 | (Ajeil et al., 2020) | Hybrid Particle Swarm Optimization - Modified Firefly (PSO-MFB) | This study focused on optimizing multiple objectives in autonomous robot navigation, such as distance, time, and safety. | The hybrid algorithm effectively balanced multiple objectives, demonstrating superior performance in path quality compared to traditional methods. |
| 3 | (Y. Li et al., 2020) | Improved Genetic Algorithm (GA) | By altering the evolutionary algorithm architecture, this study seeks to increase path planning efficiency. | The findings demonstrated that the suggested approach achieved better path optimization results compared to traditional genetic algorithms. |
| 4 | (M N A Wahab et al., 2020b) | Hybrid PSO-FS Algorithm | This paper aims to develop an efficient algorithm for mobile robots navigating in unfamiliar areas, the hybrid particle swarm optimization with firefly search (PSOFS) method is employed as a path planning technique. | The hybrid PSOFS algorithm outperformed standalone PSO and firefly search algorithms regarding the length of the path, smoothness, and computational efficiency when tested in unknown indoor environments. |

**Tab. 2. Literature of some studies in path planning using metaheuristic algorithms, continued**

| # | References | Algorithm | Short description | Results and findings |
|---|---|---|---|---|
| 5 | (G. Xu et al., 2020) | Adaptive Dynamic Firefly Algorithm | The aims of this investigation is to increase path planning's effectiveness in dynamic environments by adapting the firefly algorithm to account for moving obstacles. | The adaptive algorithm demonstrated improved pathfinding capabilities, yielding shorter paths and better obstacle avoidance compared to traditional methods. |
| 6 | (Panda et al., 2020) | Oppositional-Based Improved Firefly Algorithm | The paper focused on enhancing the firefly algorithm by introducing an oppositional-based approach to improve pathfinding in complex settings. | The outcomes demonstrated that the suggested approach effectively navigated through cluttered environments, achieving optimal paths with reduced computation time compared to standard firefly algorithms. |
| 7 | (Mohanty, 2020) | Smart Cuckoo Search Algorithm | This work aimed to develop an intelligent navigation approach for mobile robots by utilizing an enhanced cuckoo search algorithm. | The smart cuckoo search algorithm effectively navigated through uncertain environments, achieving optimal paths while minimizing computational overhead compared to traditional methods. |
| 8 | (Singh et al., 2021) | Improvised Cuckoo Search Algorithm | The authors aim to reduce the traverse space and computation time | Reducing Robot Path Planning Computation Time |
| 9 | (Yuan et al., 2022) | Improved PSO | By employing an enhanced PSO technique that improves convergence and solution quality, the study seeks to improve path planning techniques for mobile robots. | Findings revealed that the enhanced PSO significantly reduced path length and improved success rates in various scenarios. |
| 10 | (Kumar & Sikander, 2022) | Improved Artificial Bee Colony Algorithm | This research focused on optimizing mobile robot navigation through innovative algorithmic strategies. | The suggested approach successfully reduced path length and improved navigation efficiency in complicated situations, according to the results. |
| 11 | (F.-F. Li et al., 2022) | Improved artificial fish swarm algorithm | The aims of this study is to enhance the efficiency and smoothness of robot navigation utilizing an optimized AFS algorithm. | The improved algorithm successfully generated smooth paths while avoiding obstacles and minimizing path length, outperforming standard artificial fish swarm methods. |
| 12 | (Rodríguez-Molina et al., 2022) | Online Metaheuristic Optimization | This study focused on developing an online optimization strategy that can adapt path planning in real-time for differential drive robots in dynamic environments. | The online metaheuristic optimization method successfully generated optimal paths in real-time while adapting to changes in the environment. Results from experiments on a differential drive robot validated the effectiveness of the approach. |
| 13 | (Zhang et al., 2022) | PSO - FA particle swarm optimization and the firefly algorithm | The main aim of this research is to formulate an efficient hybrid algorithm so that path planning can appreciate the benefits of a few optimization techniques. | Results showed that the hybrid algorithm effectively minimized path length, improved smoothness, and enhanced computational efficiency compared to individual optimization techniques. |

**Tab. 2. Literature of some studies in path planning using metaheuristic algorithms, continued**

| # | References | Algorithm | Short description | Results and findings |
|---|---|---|---|---|
| 14 | (Abdul Khaleq et al., 2022) | Intelligent Hybrid Path Planning Algorithms | This research explored the development and application of hybrid algorithms that combine multiple optimization techniques to enhance path planning for autonomous robots. | The results manifest that intelligent hybrid algorithms can considerably improve the performance of path planning in terms of optimization over several variables, such as smoothness and computational cost, as compared to individual optimization methods. |
| 15 | (Kumar et al., 2022) | Modified Cuckoo Search Algorithm | This study focused on improving path optimization and control mechanisms for mobile robots utilizing an altered Cuckoo search algorithm. | Findings indicate that the modified cuckoo search algorithm effectively minimized path lengths and enhanced control performance, outperforming traditional optimization methods. |
| 16 | (Garip et al., 2022) | Firefly Algorithm FA, PSO, and Cuckoo Search (CS) | Optimizing path planning for mobile robots is the goal of this study, by integrating multiple algorithms to leverage their strengths. | The hybrid approach showed significant improvements in path planning efficiency, showing superior performance over individual algorithms in terms of path length and calculation time. |
| 17 | (Abu et al., 2023) | Improved Genetic Algorithms (GA) | This paper focused on refining genetic algorithms to enhance pathfinding efficiency and effectiveness in autonomous navigation. | The results showed that the improved GA minimized path length and execution time, outperforming standard GA approaches. |
| 18 | (Dai et al., 2023) | Novel Whale Optimization Algorithm | The study explored a new optimization strategy inspired by whale behavior to improve navigation efficiency in robots. | The results indicated that the whale optimization algorithm provided optimal paths with reduced computational costs and enhanced navigation efficiency. |
| 19 | (H. Li et al., 2023) | Improved Hybrid Artificial Fish Swarm Algorithm | The paper focused on developing an efficient path planning strategy for AGVs in dynamic environments using a hybrid artificial fish swarm approach. | The proposed hybrid algorithm outperformed standalone artificial fish swarm and other optimization methods in terms of path length, smoothness, and convergence speed. |
| 20 | (Zou et al., 2023) | Enhanced Dynamic Window Method and Mayfly Optimization Algorithm | This study aims to enhance mobile robot navigation by integrating mayfly optimization with dynamic window techniques to handle real-time obstacles. | The hybrid approach yielded superior path planning results, exhibiting improved effectiveness in path optimization and obstacle avoidance in dynamic situations. |
| 21 | (Tian et al., 2024) | Hybrid Whale Optimization with Firefly Algorithm | This paper aims to attain better path optimization in robotic navigation, combine the advantages of both approaches. | Findings show that the hybrid approach significantly improved path quality and reduced planning time compared to standalone algorithms. |
| 22 | (Abed & Jasim, 2024) | Bat Algorithm | This paper aims to develop a bat algorithm-based strategy that can handle multiple objectives and moving targets in robot path planning. | The proposed method was able to produce optimal paths based on multiple criteria including distance, time, and safety while achieving the movement of the target. The results of the simulation revealed how well the bat algorithm performed in scenarios related to multi-objective path planning. |

## 5. PERFORMANCE METRICS

Table 3 presents a comparative analysis of 22 metaheuristic algorithms used in mobile robot path planning, evaluated based on five critical metrics: path length, convergence speed, computation time, success rate, and smoothness. The data show that hybrid algorithms generally outperform standalone techniques in terms of overall efficiency and reliability. For example, the WOA-FF algorithm achieves the shortest path length and fastest convergence with a high success rate, making it one of the top performing approaches. Similarly, Hybrid AFSA and PSO-FA provide a balanced tradeoff between path quality and computational efficiency. On the other hand, traditional algorithms such as Improvised Cuckoo and Smart Cuckoo show lower performance in smoothness and success rate, indicating their limitations in dynamic or complex environments. The table shows that no single algorithm excels in all metrics, but hybridization strategies tend to improve adaptability and overall performance, making them promising solutions for real-world path planning challenges. It should be noted that the performance metrics presented in Table 3 are extracted from the respective original studies; therefore, the values reflect results obtained in different experimental environments and serve to illustrate relative performance trends rather than results from a unified implementation.

**Tab. 3. Literature of some studies in path planning using metaheuristic algorithms**

| No. | Algorithm | Path Length (cm) | Convergence Speed (iterations) | Computational Time (s) | Success Rate (%) | Smoothness (curvature) |
|---|---|---|---|---|---|---|
| 1 | EH-ACO (Gao et al., 2020) | 562.7 | 50 | 2.3 | 95 | 0.2463 |
| 2 | PSO-MFB (Ajeil et al., 2020) | 456.7 | 40 | 1.5 | 90 | 0.5873 |
| 3 | Improved GA (Li et al., 2020) | 462.9 | 48 | 1.9 | 94 | 0.0120 |
| 4 | Dynamic FA (Y. Xu et al., 2020) | 315.0 | 47 | 1.8 | 90 | 0.2550 |
| 5 | Oppositional FA (Panda et al., 2020) | 340.5 | 54 | 1.9 | 89 | 0.2350 |
| 6 | Smart Cuckoo (Mohanty, 2020) | 395.8 | 54 | 1.8 | 89 | 0.2900 |
| 7 | Hybrid PSO-FS (Wahab et al., 2020b) | 330.0 | 52 | 1.7 | 95 | 0.2600 |
| 8 | Improvised Cuckoo (Singh et al., 2021) | 430.1 | 56 | 2.2 | 90 | 0.3100 |
| 9 | Improved PSO (Yuan et al., 2022) | 395.7 | 55 | 2.0 | 92 | 0.4007 |
| 10 | ABC-EP (Kumar et al, 2022) | 292.0 | 42 | 1.7 | 89 | 0.0718 |
| 11 | AFSA (Li et al., 2022) | 216.0 | 38 | 1.4 | 88 | 0.5873 |
| 12 | Online Metaheuristic (Rodríguez-Molina et al., 2022) | 310.0 | 60 | 2.4 | 94 | 0.2000 |
| 13 | PSO-FA (Zhang et al., 2022) | 300.5 | 45 | 1.8 | 92 | 0.2150 |
| 14 | Hybrid ACO-PSO (Abdul Khaleq, 2022) | 350.0 | 50 | 2.0 | 90 | 0.2400 |
| 15 | Cuckoo Search (Kumar et al., 2022) | 360.0 | 58 | 2.2 | 93 | 0.2700 |
| 16 | FA-PSO-CS (Garip et al., 2022) | 292.0 | 42 | 1.7 | 89 | 0.0718 |
| 17 | Improved GA (Abu et al., 2023) | 429.9 | 60 | 2.5 | 91 | 0.0718 |
| 18 | Novel WOA (Dai et al., 2023) | 359.9 | 52 | 2.1 | 96 | 0.0140 |
| 19 | Hybrid AFSA (Li et al., 2023) | 230.5 | 43 | 1.6 | 92 | 0.1920 |
| 20 | MOA-DWA (Zou et al., 2023) | 335.0 | 49 | 1.5 | 91 | 0.2200 |
| 21 | WOA-FF (Tian et al., 2024) | 283.0 | 35 | 1.2 | 97 | 0.0846 |
| 22 | Bat (Abed & Jasim, 2024) | 340.0 | 55 | 2.1 | 93 | 0.2500 |

where:

- Path length**:** total Euclidean distance of the planned path from the start point to the target point.
- Convergence Speed: requiring iterations to reach an optimal solution.
- Computational Time: average computational times depending on the complexity.
- Success Rate: successfully navigating through obstacles in test scenarios.
- Smooth of paths: reducing sharp turns and enhancing navigability.

## 6. DISCUSSION

Tables 2 and 3 present a comprehensive summary of numerous research studies focused on improving mobile robot path planning algorithms. The studies primarily explore improvements to established optimization algorithms such as Whale Optimization Algorithms (WOA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Genetic Algorithms (GA), and others. These algorithms are critical to the navigation of mobile robots, especially in dynamic and complex environments. Several studies, including those by Gao et al. (2020) and Zhou & Wei, focus on improving ACO by introducing new pheromone update mechanisms and adaptive strategies. These enhancements aim to increase convergence speed and reduce path inflection points, resulting in smoother and more efficient navigation paths for robots. Research by Yuan et al. (2022) highlights the combination of PSO with other optimization techniques to balance multiple objectives in path planning. The results of the simulation experiments show large improvements in the quality and efficiency of the path. This confirms that PSO is flexible and can be applied in many scenarios. In the studies by Abu et al. (2023) and Li et al., GA frameworks are extended with improvements in path lengths and execution times needed to optimize robot navigation in real-time applications.

An important trend in this research direction is hybrid algorithms, which combine several optimization techniques. One of the excellent combinations is the Whale and Firefly algorithms, which have been able to produce high quality paths with less planning time than standalone algorithms. It uses many of the advantages of different algorithms to improve performance in path planning tasks. Several studies involve the development of algorithms that work under dynamic scenarios, such as those of Rodríguez-Molina et al. (2022) and G. Xu et al. (2020). The algorithms combine real-time strategies for optimization by dealing with movement in obstacles around the robots, which significantly improve the navigation capabilities of these robots.

Figures 5 and 6 present a comparative analysis of 22 metaheuristic algorithms for mobile robot path planning based on five key performance metrics: path length, convergence speed, computation time, success rate, and smoothness. The metrics have been normalized to allow fair comparison across different scales. As shown in the figure, the Hybrid Whale Optimization with Firefly Algorithm (WOA-FF) shows superior overall performance, with high scores in path length efficiency, fast convergence, and minimal computation time, making it one of the most balanced and effective approaches. The Improved Artificial Fish Swarm Algorithm (AFSA) and its hybrid variant also show strong results, especially in generating smoother paths. On the other hand, algorithms such as Improvised Cuckoo Search and MOA-DWA show comparatively lower performance in most metrics, indicating limitations in either solution quality or computational efficiency. The figures also reveal a general trend where hybrid algorithms consistently outperform their standalone counterparts, underscoring the value of combining multiple optimization strategies. This visual comparison provides clear insights for selecting appropriate algorithms based on application-specific needs and constraints.

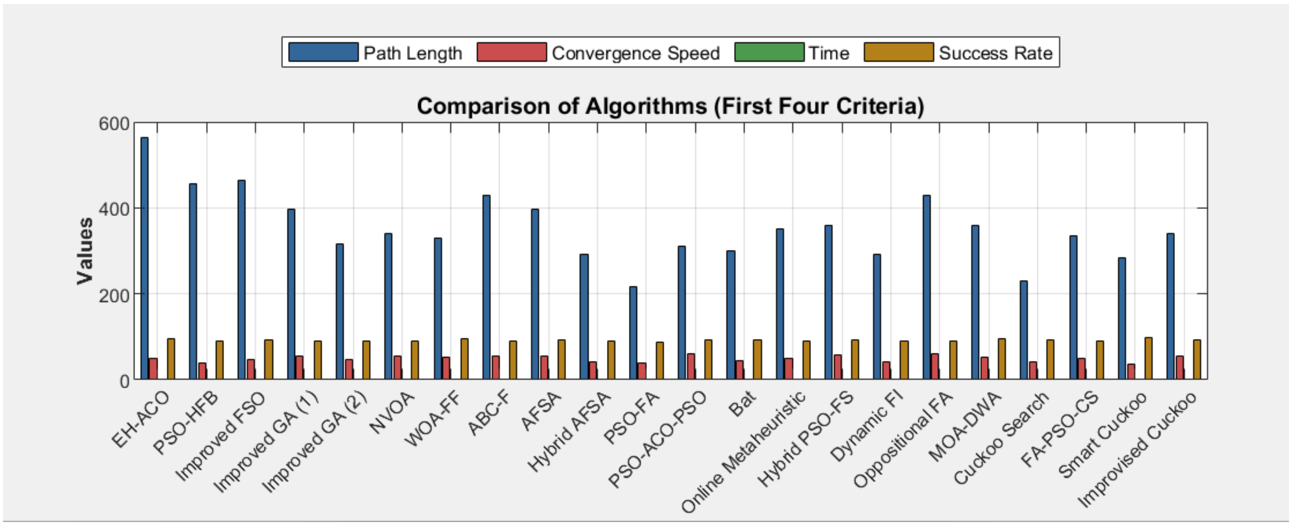


**Fig. 5. Comparison of 22 metaheuristic algorithms for path planning based on path length, convergence speed, computational time, and success rate**

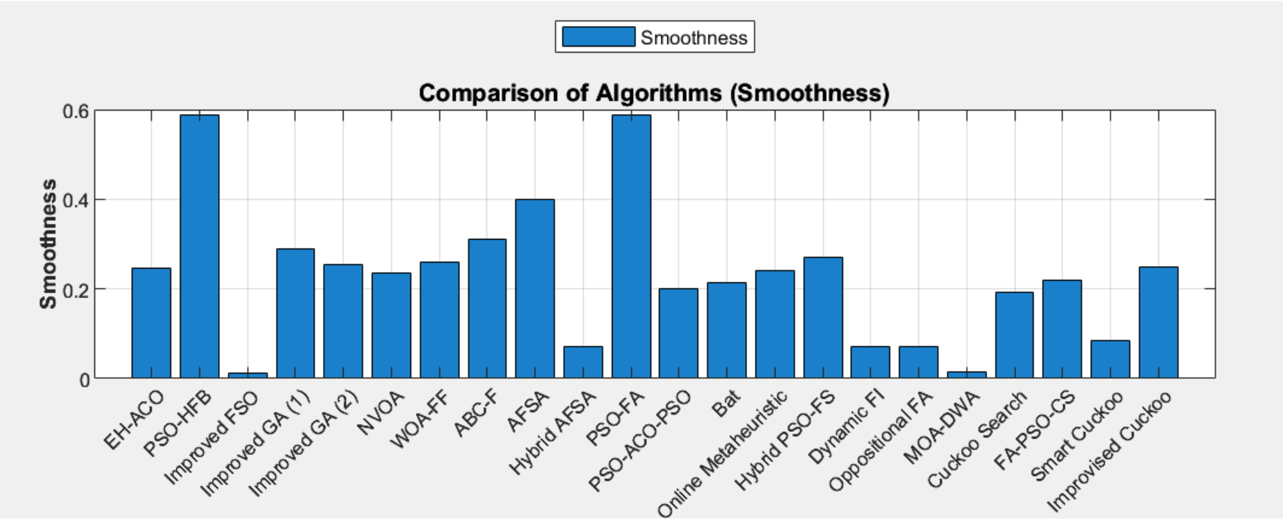


**Fig. 6. Comparison of 22 metaheuristic algorithms for path planning by smoothness**

Results from multiple studies show that the improved algorithms consistently outperform traditional methods on several key performance metrics, including

1. Path length: Most improvements result in shorter paths, which is important for navigation efficiency.
2. Smoothing: Improved algorithms smoothen the path; this would reduce jerky motion, which leads to robot performance.

## 7. CHALLENGES AND FUTURE DIRECTIONS

### 7.1. Challenges

1. Handling Uncertainty: The challenge of uncertainty, incomplete information, or changes in an environment can occur unexpectedly; finding robust algorithms to handle such cases remains a challenge.
2. Real-time adaptability: In practical applications, it is very important to improve the algorithms to handle dynamic obstacles and real-time changes in the environment.
3. Multi-Objective Optimization: Multi-objective optimization considers multiple objectives simultaneously, such as path length, energy consumption, and safety, which is computationally intensive.
4. Computational efficiency: Computation time should be minimized with sufficient path quality to achieve real-time decision making, especially in large or cluttered environments.

### 7.2. Future directions

1. Hybrid Algorithms: Combining different metaheuristic algorithms can realize the strengths of each algorithm and overcome their individual weaknesses, which is a very promising direction to improve the performance of path planning.
2. Adaptation Strategies: Designing algorithms that can self-tune their parameters according to the environment will increase their adaptability and efficiency.
3. Integration with machine learning: Integration with metaheuristic algorithms will greatly enhance their decision-making potential and adaptability to change. This integration finds its application especially in deep reinforcement learning.
4. Hardware Implementation: The practical utility of metaheuristic algorithms needs to be further validated by testing their performance on real robotic systems and in a physical environment. Standardization and Benchmarking Standard benchmarking and comparable criteria will allow for proper comparison between different metaheuristic algorithms, which will be a major step forward in the advancement of the field.

## 8. CONCLUSIONS

In the field of mobile robotics, metal algorithms have proven to be useful tools for solving complex path planning problems. Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Whale Optimization Algorithms (WOA), and other optimization techniques are covered in this review. Each of these approaches has a particular advantage when it comes to solving the mobility problems faced by mobile robots. For example, ACO shows strong performance in complex environments with multiple obstacles due to its ability to explore multiple paths in parallel. PSO is efficient in convergence speed, making it suitable for real-time path planning. GWO provides a good balance between exploration and exploitation, which helps to avoid local minima.

The main results of the studies indicate that the development and improvement of traditional algorithms, such as adaptive strategies and hybrid methods, led to significant improvements in performance metrics, including path length, computational efficiency, and smoothness. For example, PSO combined with multi-objective Firefly algorithms demonstrated faster convergence and better navigation capabilities in dynamic environments, while the introduction of new pheromone update mechanisms in ACO increased algorithm efficiency. Despite all these developments, many difficulties and challenges remain, such as dealing with uncertainty in dynamic environments, achieving real-time adaptability, and balancing multiple objectives. Moreover, most of the algorithms urgently need to improve their computational efficiency in order to make faster decisions in practical scenarios.

Therefore, future perspectives include exploiting the strengths of different optimization techniques, developing hybrid algorithms, embedding machine learning to improve adaptability, and the need for validation in real-world scenarios, which calls for more uniform standards in performance evaluation.

### Conflicts of Interest

*The authors declare no conflict of interest.*

### REFERENCES


Abdul Khaleq, N., & Al-Araji, A. (2022). Intelligent hybrid path planning algorithms for autonomous mobile robots. *International Journal of Intelligent Engineering and Systems*, *15*(5), 309–325. doi: 10.22266/ijies2022.1031.28

Abdulsaheb, J. A., & Kadhim, D. J. (2023). Classical and heuristic approaches for mobile robot path planning: A survey. *Robotics*, *12*(4), 93. https://doi.org/10.3390/robotics12040093

Abed, B. M., & Jasim, W. M. (2024). Multi-objective path planning optimization with moving target based on bat algorithm. *AIP Conference Proceedings*, *3009*, 20005. https://doi.org/10.1063/5.0193586

Abed, M. S., Lutfy, O. F., & Al-Doori, Q. F. (2021). A review on path planning algorithms for mobile robots. *Engineering and Technology Journal*, *39*(05), 804-820. https://doi.org/10.30684/etj.v39i5A.1941

Abu, N., Bukhari, W., Adli, M., & Ma'Arif, A. (2023). Optimization of an autonomous mobile robot path planning based on improved genetic algorithms. *Journal of Robotics and Control (JRC)*, *4*(4), 557-571q. https://doi.org/10.18196/jrc.v4i4.19306

Ahmad, J., Wahab, M. N. A., Ramli, A., Misro, M. Y., Ezza, W. Z., & Hasan, W. Z. W. (2026). Enhancing performance of global path planning for mobile robot through Alpha–Beta Guided Particle Swarm Optimization (ABGPSO) algorithm. *Measurement*, *257*, 118633. doi: https://doi.org/10.1016/j.measurement.2025.118633

Ajeil, F. H., Ibraheem, I. K., Sahib, M. A., & Humaidi, A. J. (2020). Multi-objective path planning of an autonomous mobile robot using hybrid PSO-MFB optimization algorithm. *Applied Soft Computing*, *89*, 106076. https://doi.org/10.1016/j.asoc.2020.106076

Alhaqbani, A., Kurdi, H. A., & Hosny, M. J. A. O. C. M. I. E. (2022). Fish-inspired heuristics: a survey of the state-of-the-art methods. *29*, 3655–3675. https://doi.org/10.1007/s11831-022-09711-0

Awadallah, M. A., Makhadmeh, S. N., Al-Betar, M. A., Dalbah, L. M., Al-Redhaei, A., Kouka, S., & Enshassi, O. S. (2025). Multi-objective ant colony optimization: Review. *Archives of Computational Methods in Engineering*, *32*(2), 995–1037. https://doi.org/10.1007/s11831-024-10178-4

Dai, Y., Yu, J., Zhang, C., Zhan, B., & Zheng, X. (2023). A novel whale optimization algorithm of path planning strategy for mobile robots. *Applied Intelligence*, *53*. 10843–10857. https://doi.org/10.1007/s10489-022-04030-0

Dao, T.-K., & Nguyen, T.-T. (2024). A review of the bat algorithm and its varieties for industrial applications. *Unknown Journal*, 36(8), 5327-5349. https://doi.org/10.1007/s10845-024-02506-z

El-Kenawy, E.-S. M., Khan, Z. S., Ibrahim, A., Aloyaydi, B. A., Ali, H. A., & Takieldeen, A. E. (2022). Metaheuristic optimization for mobile robot navigation based on path planning. *Computers, Materials and Continua*, *73*(2), 2241-2255. https://doi.org/10.32604/cmc.2022.026672

Gad, A. G. (2022). Particle swarm optimization algorithm and its applications: A systematic review. *Archives of Computational Methods in Engineering*, *29*, 2531–2561. https://doi.org/10.1007/s11831-021-09694-4

Gao, W., Tang, Q., Ye, B., Yang, Y., & Yao, J. (2020). An enhanced heuristic ant colony optimization for mobile robot path planning. *Soft Computing*, *24*, 6139–6150. https://doi.org/10.1007/s00500-020-04749-3

Garip, Z., Karayel, D., & Erhan Çimen, M. (2022). A study on path planning optimization of mobile robots based on hybrid algorithm. *Concurrency and Computation: Practice and Experience*, *34*(5), e6721. https://doi.org/10.1002/cpe.6721

Gen, M., & Lin, L. (2023). Genetic Algorithms and Their Applications. In H. Pham (Ed.), *Springer Handbook of Engineering Statistics* (pp. 635–674). Springer London. https://doi.org/10.1007/978-1-4471-7503-2_33

Hewawasam, H., Ibrahim, M. Y., & Appuhamillage, G. K. (2022). Past, present and future of path-planning algorithms for mobile robot navigation in dynamic environments. *IEEE Open Journal of the Industrial Electronics Society*, *3*, 353-365. https://doi.org/10.1109/OJIES.2022.3179617

Kamil, A., & Mahmood, B. (2025). Integrating path planning and task scheduling in autonomous drone operations. *Applied Computer Science*, *21*(2), 1–17. doi: 10.35784/acs_6872

Karur, K., Sharma, N., Dharmatti, C., & Siegel, J. E. (2021). A survey of path planning algorithms for mobile robots. *Vehicles*, *3*(3), 448-468. https://doi.org/10.3390/vehicles3030027

Kumar, S., & Sikander, A. (2022). Optimum mobile robot path planning using improved artificial bee colony algorithm and evolutionary programming. *Arabian Journal for Science and Engineering*, *47*, 3519–3539. https://doi.org/10.1007/s13369-021-06326-8

Kumar, S., Parhi, D. R. K., Kashyap, A. K., & Vikas. (2022). Path optimization and control of mobile robot using modified cuckoo search algorithm. In B. B. V. L. Deepak, D. R. K. Parhi, B. B. Biswal, & P. C. Jena (Eds), *Applications of Computational Methods in Manufacturing and Product Design* (pp. 125–133). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0296-3_12

Li, F.-F., Du, Y., & Jia, K.-J. (2022). Path planning and smoothing of mobile robot based on improved artificial fish swarm algorithm. *Scientific Reports*, *12*, 659. https://doi.org/10.1038/s41598-021-04506-y

Li, H., Sun, Z., & Luo, M. (2023). AGV path planning based on improved hybrid artificial fish swarm algorithm. *2023 IEEE 11th Joint International Information Technology and Artificial Intelligence Conference (ITAIC)*, (pp. 1676–1681). IEEE. https://doi.org/10.1109/ITAIC58329.2023.10409092

Li, Y., Huang, Z., & Xie, Y. (2020). Path planning of mobile robot based on improved genetic algorithm. *2020 3rd International Conference on Electron Device and Mechanical Engineering (ICEDME)* (pp. 691–695). IEEE. https://doi.org/10.1109/ICEDME50972.2020.00163

Liu, L, Wang, X., Yang, X., Liu, H., Li, J., & Wang, P. (2023). Path planning techniques for mobile robots: Review and prospect. *Expert Systems with Applications*, *227*, 120254. https://doi.org/10.1016/j.eswa.2023.120254

Makhadmeh, S. N., Alomari, O. A., Mirjalili, S., Al-Betar, M. A., Elnagar, A. J. N. C., & Applications. (2022). Recent advances in multi-objective grey wolf optimizer, its versions and applications. *34*, 19723–19749, https://doi.org/10.1007/s00521-022-07704-5

Mohanty, P. K. (2020). An intelligent navigational strategy for mobile robots in uncertain environments using smart cuckoo search algorithm. *Journal of Ambient Intelligence and Humanized Computing*, *11*, 6387–6402. https://doi.org/10.1007/s12652-020-02535-5

Montiel, O., Orozco-Rosas, U., & Sepúlveda, R. (2015). Path planning for mobile robots using bacterial potential field for avoiding static and dynamic obstacles. *Expert Systems with Applications*, *42*(11), 5177-5191. https://doi.org/10.1016/j.eswa.2015.02.033

Panda, M. R., Panda, S., Priyadarshini, R., & Das, P. (2020). Mobile robot path-planning using oppositional-based improved firefly algorithm under cluttered environment. In M. N. Mohanty & S. Das (Eds), *Advances in Intelligent Computing and Communication* (Vol. 109, pp. 141–151). Springer Singapore. https://doi.org/10.1007/978-981-15-2774-6_18

Promkaew, N., Thammawiset, S., Srisan, P., Sanitchon, P., Tummawai, T., & Sukpancharoen, S. (2024). Development of metaheuristic algorithms for efficient path planning of autonomous mobile robots in indoor environments. *Results in Engineering*, *22*, 102280. doi: https://doi.org/10.1016/j.rineng.2024.102280

Rafai, A. N. A., Adzhar, N., & Jaini, N. I. (2022). A review on path planning and obstacle avoidance algorithms for autonomous mobile robots. *Journal of Robotics*, *2022*, 2538220. https://doi.org/10.1155/2022/2538220

Rodríguez-Molina, A., Herroz-Herrera, A., Aldape-Pérez, M., Flores-Caballero, G., & Antón-Vargas, J. A. (2022). Dynamic path planning for the differential drive mobile robot based on online metaheuristic optimization. *Mathematics*, *10*(21), 3990. https://doi.org/10.3390/math10213990

Sadeeq, H T, & Abdulazeez, A. M. (2022). Giant Trevally Optimizer (GTO): A novel metaheuristic algorithm for global optimization and challenging engineering problems. *IEEE Access*, *10*, 121615–121640. https://10.1109/ACCESS.2022.3223388

Sadeeq, H T, Abdulazeez, A. M. J. I. J. O. O., & Engineering, B. (2023). Metaheuristics: A review of algorithms. *International Journal of Online and Biomedical Engineering*. *19*(09), 142–164. https://doi.org/10.3991/ijoe.v19i09.39683

Sadeeq, Haval T. (2025). Cauchy operator boosted artificial rabbits optimization for solving power system problems. *Eng*, *6*(8), 174. https://doi.org/10.3390/eng6080174

Sadeeq, Haval Tariq, & Abdulazeez, A. M. (2023). Car side impact design optimization problem using giant trevally optimizer. *Structures*, *55*, 39–45. https://doi.org/10.1016/j.istruc.2023.06.016

Sadeeq, Haval Tariq, Abrahim, A., Hameed, T., Kako, N., Mohammed, R., & Ahmed, D. (2025). An improved pelican optimization algorithm for function optimization and constrained engineering design problems. *Decision Science Letters*, *14*(3), 623–640. https://doi.org/10.5267/j.dsl.2025.4.004

Saeed, R. A., Recupero, D. R., & Remagnino, P. (2020). A boundary node method for path planning of mobile robots. *Robotics and Autonomous Systems*, *123*, 103320. https://doi.org/10.1016/j.robot.2019.103320

Sánchez-Ibáñez, J. R., Pérez-Del-Pulgar, C. J., & García-Cerezo, A. (2021). Path planning for autonomous mobile robots: A review. *Sensors*. *21*(23), 7898. https://doi.org/10.3390/s21237898

Singh, S., Sharma, K., & Doriya, R. (2021). Minimizing computation time for robot path planning using improvised cuckoo search algorithm. In T. Sengodan, M. Murugappan, & S. Misra (Eds), *Advances in Electrical and Computer Technologies* (Vol. 711, pp. 199–209). Springer Nature Singapore. https://doi.org/10.1007/978-981-15-9019-1_18

Teja, G Krishna, Mohanty, Prases K, & Das, Shubhajit. (2025). Review on path planning methods for mobile robot. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *239*(14), 5547–5580. https://doi.org/10.1177/09544062251330083

Tian, T., Liang, Z., Wei, Y., Luo, Q., & Zhou, Y. (2024). Hybrid whale optimization with a firefly algorithm for function optimization and mobile robot path planning. *Biomimetics*, *9*(1), 39; https://doi.org/10.3390/biomimetics9010039

Wahab, M. N. A., Lee, C. M., Akbar, M. F., & Hassan, F. H. (2020a). Path planning for mobile robot navigation in unknown indoor environments using hybrid PSOFS algorithm. *IEEE Access*, *8*, 161805–161815. https://doi.org/10.1109/ACCESS.2020.3021605

Wahab, M. N. A., Nefti-Meziani, S., & Atyabi, A. (2020b). A comparative review on mobile robot path planning: Classical or meta-heuristic methods? *Annual Reviews in Control*, *50*, 233–252. https://doi.org/10.1016/j.arcontrol.2020.10.001

Xu, G., Zhang, T.-W., Lai, Q., Pan, J., Fu, B., & Zhao, X. (2020). A new path planning method of mobile robot based on adaptive dynamic firefly algorithm. *Modern Physics Letters B*, *34*(29), 2050322. https://doi.org/10.1142/S0217984920503224

Xu, Y., Li, Q., Xu, X., Yang, J., & Chen, Y. (2023). Research progress of nature-inspired metaheuristic algorithms in mobile robot path planning. *Electronics*, *12*(15), 3263. https://doi.org/10.3390/electronics12153263

Yahia, H. S., & Mohammed, A. S. (2023). Path planning optimization in unmanned aerial vehicles using meta-heuristic algorithms: a systematic review. *Environmental Monitoring and Assessment*, *195*(1). https://doi.org/10.1007/s10661-022-10590-y

Yang, L., Li, P., Qian, S., Quan, H., Miao, J., Liu, M., Hu, Y., & Memetimin, E. (2023). Path planning technique for mobile robots: A review. *Machines*, *11*, 980. https://doi.org/10.3390/machines11100980

Yang, X.-S. (2020). *Nature-Inspired Optimization Algorithms: Second Edition*. Academic Press.

Yuan, Q., Sun, R., & Du, X. (2022). Path planning of mobile robots based on an improved particle swarm optimization algorithm. *Processes*. *11*(1), 26. https://doi.org/10.3390/pr11010026

Zhang, T.-W., Xu, G.-H., Zhan, X.-S., & Han, T. (2022). A new hybrid algorithm for path planning of mobile robot. *The Journal of Supercomputing*, *78*, 4158–4181. https://doi.org/10.1007/s11227-021-04031-9

Zidani, G., Djarah, D., Benmakhlouf, A., & Khettache, L. (2024). Optimizing pedestrian tracking for robust perception with YOLOv8 and deepsort. *Applied Computer Science*, *20*(1), 72–84, https://doi.org/10.35784/acs-2024-05

Zou, A., Wang, L., Li, W., Cai, J., Wang, H., & Tan, T. (2023). Mobile robot path planning using improved mayfly optimization algorithm and dynamic window approach. *The Journal of Supercomputing*, *79*, 8340–8367. https://doi.org/10.1007/s11227-022-04998-z