Research progress of path planning algorithm for mobile robot navigation

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Abstract. The main research contents of mobile robot technology include: navigation and positioning, path planning and motion control. Path planning is an important branch of mobile robot research. Its task is to find an optimal path in its workspace according to some optimization criteria. Many different path planning algorithms have been developed to solve the corresponding problems, such as improving the safety of the path, enhancing the working ability of the robot and improving the efficiency of path planning. However, a single original path planning algorithm often has different advantages and disadvantages. Therefore, many scholars have made improvements for the defects of various algorithms According to the design principle of path planning algorithm, this article divides the mainstream path planning algorithm into three types: graph-search-based algorithm, potential field-based algorithm and intelligent bionic-based algorithm. The principle of the path planning algorithm mentioned in this paper is briefly described and the characteristics of different improved algorithms are summarized. The future research directions are prospected from three aspects: adaptability and intelligence, fusion of multiple optimization algorithms and interdisciplinary technologies integration. This article provides a reference for relevant researchers to understand the ideas of related improved algorithms.

Keywords: mobile robot, path planning, graph-search-based algorithm, intelligent bionic-based algorithm, potential field-based algorithm.

1. Introduction

With the continuous updating of science and technology, mobile robots have not only been the key research topic in the field of artificial intelligence, but have also penetrated into various fields of life. The main research of mobile robot technology includes three parts: navigation and localization, path planning and motion control [1]. Path planning as a key technology in the field of robotics has also been a hot area of research. The optimal path planning for mobile robots aims to intelligently plan the best travel path from the starting point to the target point in their complex and variable working environment. It is always based on certain optimization criteria, such as minimizing the cost of the work, shortest path length or shortest travel time [2]. Therefore, path planning for mobile robots is critical. For example, mobile robots are responsible for the transportation and handling of materials in automated factories. Path planning can ensure that robots travel quickly and safely in complex workshop environments, reducing material transportation time and increasing production efficiency. If the path planning is improper, the robot may collide with equipment or personnel, resulting in production interruptions and safety hazards. Among the path planning algorithms, A* Algorithm, Dijkstra's Algorithm, Ant Colony Algorithm and Exploring Random Tree Algorithm are commonly used algorithms for path planning [3-6]. According to different classification criteria, path planning algorithms can be categorized into global path planning algorithms and local path planning algorithms [7]. Another, path planning algorithms can also be categorized into graph-based search, potential field-based, and intelligent bionic path planning algorithm [8]. The proposal of these algorithms has greatly promoted technological innovation and industrial upgrading in the field of path planning. Compared with the more primitive algorithms, the above algorithms can improve the efficiency and accuracy of path planning to different degrees, optimize the use of resources and reduce the cost. Considering the safety of the actual work, they can also reduce the risk of accidents.

Through optimizing different algorithms, the obstacle avoidance ability, search efficiency and planning accuracy of mobile robots can be improved. However, with the deepening study of various algorithms, different algorithms reflect their superiority and limitations. For example, the traditional RRT algorithm has low running efficiency, the planned path is not optimal due to the large randomness and the artificial potential field method is prone to fail to find the path due to low gravity, etc. [9-10]. Therefore, in practical applications, different algorithms are influenced by various factors, reflecting different characteristics.

In this article, the path planning algorithms for mobile robots are categorized into graph-based search, potential field-based, and intelligent bionic path planning algorithm according to their characteristics [1,8]. The different path planning optimization algorithms in recent years are introduced, while their characteristics are summarized, and finally outlook for future path planning algorithm optimization.

2. Main Body

2.1. Path Planning Algorithm Based on Graph Search

Graph search algorithms are algorithms for traversing or searching graph structures. In path planning, graph-based search algorithms are usually used in low dimensional spaces, typically in the form of raster maps to completely represent the entire environment map. They have the characteristics of simple, effective, and easy to modify [11].

2.1.1. A* Algorithm

The A* algorithm was published by Hart et al in 1968 [3]. It is a heuristic search algorithm that reduces unnecessary searches and improves the search efficiency. It is mainly used in graph search to find the least costly path from the starting point to the target point.

Compared to the traditional A* algorithm, Yang et al. proposed three improvements: excluding all forced neighboring nodes, extracting the crucial turning points to reducing path redundancies and the number of robot's steering, and using Bezier curves to achieve segmental smoothing [12]. Four sets of simulations from different perspectives show that the above improvements compared with the original A* algorithm, the security exhibits an average 33.68% enhancement in path safety on average and the number of turning points is reduced by 37.00% on average. Additionally, the path is smoother. Wang Hai-qun et al. proposed a new dynamic measurement heuristic A * algorithm [13]. He established a grid map and added new adjustment factors to address the situation where there are many inflection points in the path obtained by the traditional A * algorithm. After simulation experiment data analysis, the number of inflection points has been reduced. In addition, it can significantly improve search efficiency and shorten path length. To solve problems about large search range and collision path in global path planning, Zhang Wei et al. proposed an improved A*algorithm is devised ground on thought of adaptive search distance [14]. The search distance is adaptively adjusted according to the complexity of the environment to reduce the number of extended search nodes and search time. Build up an anti-collision distance function to the cost function of the improved A * algorithm. Through simulation and actual testing, the results show that the improved A * algorithm optimizes the number of search nodes, iteration times, and total turning angle in the path planning stage. Xu Jianmin et al. proposed a fusion algorithm based on the A* algorithm of the Multi-scale Map Approach and the improved Dynamic Window Approach (DWA) algorithm [15]. The fusion algorithm can address the issues of sharply increasing computational and time costs and poor flexibility in large-scale complex environments. The A * algorithm is developed by establishing a multi-scale set, adding an obstacle proportion factor to the heuristic function and using the Floyd algorithm to optimize the nodes. Besides, the heading angle adaptive adjustment strategy and parking wait state are added to optimize the dynamic window method. After the ROS simulation and actual vehicle experiments, the fusion algorithm enables mobile robot to have higher flexibility and adaptability, and it can greatly shorten search time and improve search efficiency.

2.1.2. Dynamic A* Algorithm

The D*(Dynamic A*) algorithm was proposed by Sven Koenig and Maxim Likhachev in 2002 [16]. It is suitable for dynamic environments and continuously updates the proxy value of each node in the path. When there are new node changes, it can immediately determine the new shortest path [17].

In unknown and complex environment, traditional D* algorithm have problems of blind search, low computational efficiency, and difficulty in obtaining safe trajectories. Ju Muhan et al. proposed an improved D* algorithm, incorporating the idea of jump point search into front-end path planning to improve planning efficiency [18]. Based on the B-spline, the back-end construct a quadratic planning problem to simplify the difficulty of solving. The results show that comparing with the traditional D * algorithm, Focused D * algorithm, and directed D * algorithm, the number of search nodes and search time have been optimized to varying degrees. In order to solve the problems of low algorithm efficiency and complex inflection points in the use of traditional D* algorithm for the unmanned aerial vehicle, Wang Xiaoshuai et al. adopted a variable step size approach in selecting extension nodes which accelerates the traversal speed of nodes [19]. In addition, the fusion formula of Chebyshev distance and Manhattan distance replaces the traditional Euclidean distance, reducing computational complexity and improving efficiency. Through MATLAB simulation, the performance of the improved D* algorithm in three-dimensional experimental environments is more efficient, path safety is improved, and path complexity is reduced.

2.2. Path planning algorithm based on potential field

The Artificial Potential Field (APF) method was proposed by Khatib in 1985. This algorithm sets the target point to have attraction on the robot, while obstacles have repulsion on the robot [20]. The direction of the resultant force represents the expected direction of motion, and the magnitude of the resultant force represents the desired speed. This algorithm has the characteristics of simple structure and convenient real-time control [21].

To solve the local minimization and trajectory oscillation of mining mobile robots in complex environments, Zhang Desheng proposed an improved APF method [22]. To avoid falling into the local minimum position, this method introduces virtual target points to guide the robot escape from the dead zone. By using a fuzzy controller to determine the potential field situation the method can enhance the trajectory smoothness of robot. Through MATLAB simulation, this improvement method has higher environmental adaptability and smoother path. Wu Meihua introduces the relative velocity and acceleration factors between the mobile robot and the target point into the gravity function [23]. This ensures that the mobile robot maintains the same motion trend with the target point. Introducing the radius of the obstacle and the radius of the robot to avoid collisions between mobile robots and obstacles. In order to avoid the robot getting stuck in local minimization, the center line method is proposed to change the resultant force on the robot. The improved algorithm has been proven effective through MATLAB simulation. Aiming at the difficulty of path planning for mobile robots in complex environments, Shi Weiguo et al. proposed a mixed ant colony potential field algorithm (MACPF) [24]. Firstly, multi-factor heuristic function and new ant travel mechanism are used to improve path quality. Secondly, the adaptive volatilization coefficient and dynamic weight coefficient are designed to accelerate convergence speed. Thirdly, traditional artificial potential field methods are prone to getting stuck in local minimization, unreachable target and excessive obstacle avoidance. This method solves these problems by introducing the concepts of virtual target point, relative distance and safe distance. Through simulation analysis, the MACPF algorithm has demonstrated strong environmental adaptability and path planning efficiency. Ní Jianyun et al. proposed an improved APF method to address the issues of unreachable targets and local minimization [25]. By introducing the distance factor between the robot and the target point, an elliptical target strategy and an elliptical tracking strategy, the optimization goal is achieved. In addition, a cubic uniform B spline curve is introduced to solve the problems of low turning efficiency and unbalanced turning points. The feasibility and effectiveness of this improved method have been confirmed through simulation.

2.3. Path Planning Algorithm Based on Intelligent Bionics

Path planning algorithm based on intelligent bionics are algorithms that mimic certain group behaviors or biological structures and utilize swarm intelligence. Its main characteristics include biomimetic features, simplicity and emergence, robustness and self-organization. [26].

2.3.1. Ant Colony Optimization

Ant Colony Optimization (ACO) was proposed by Italian scholar Dorigol in 1992 [27]. It simulates the path optimization method of ants searching for food in nature and uses pheromone precipitation and pheromone evaporation rules to search for the best path.

Xu Jianmin et al. proposed a multi-level field of view adaptive ant colony optimization (MLFVAACO) [28]. Firstly, it extends the two-level field of view on the basis of traditional AOC to make the planned path smoother. Secondly, an adaptive global initial pheromone update strategy is proposed. Thirdly, the deadlock ants in the algorithm iteration process are optimized to increase the diversity of search solutions. Finally, the state transition rule of ants is employed to avoid ants from falling into the local optimal solution. The simulation results show that the MLFVAACO algorithm performs well in terms of optimal path, ant utilization and search efficiency, while it has high adaptability to complex environments. Aiming at the slow convergence speed and tendency to fall into the local optimal solution, Xue Xiang et al. proposed a new improved algorithm [29]. Firstly, a trend heuristic function was established and the Cauchy distribution function was introduced on the basis of this function. Then, improve the distance heuristic function to make path selection more purposeful. Thirdly, Improve the pheromone volatilization factor to accelerate convergence speed. Through MATLAB simulation, this improved algorithm shows significant improvements in minimum path length, convergence speed, and smoothness compared to traditional ACO algorithms. To improve the path planning performance of rescue robots in the fire scene, Ding Jinhu proposed several measures [30]. Build indoor environment models by using BIM technology. Optimize the process of extracting and updating pheromones. Improve pheromone volatilization factor. Add probability factors to avoid obstacles. Set specific conditions to make ants jump out of the loop. Finally, determine the suitability of different escape speeds and routes for trapped individuals and select appropriate escape points. Verified by simulation experiments, this improved algorithm has fewer iterations, stronger convergence, and is suitable for complex environments.

2.3.2. Genetic Algorithms

Genetic algorithms (GA) were proposed by John Holland in the early 1970s [31]. This algorithm imitates the evolution and genetic mechanisms of nature and use operations such as screening, hybridization, and mutation. It gradually generates and optimizes the next generation of potential or optimal solutions and ultimately achieve a gradual optimization of the effect [32].

WU Yue'an et al. optimized the order of tilt-rotor unmanned aerial vehicle (TRUAV) coverage paths through the minimum spanning and back-and-forth path generation algorithms [33]. Adopting a fishtail-shaped obstacle avoidance strategy to avoid obstacles within the area. Heuristic search for coverage path order is performed using the Dubins-based enhanced genetic algorithm. Improve the generation of the initial population, design of the fitness function, crossover operator, and compilation operator. According to the simulation results, the area coverage efficiency of the tiltrotor unmanned aerial vehicle is significantly improved, and the length of the coverage path is greatly reduced. When using traditional genetic algorithms for path planning of goods transportation in logistics transit warehouses, mobile robots have problems with premature convergence and poor optimization ability. Liu Zhi-hai et al. improved it through three genetic operators: selection, crossover, and mutation [34]. The selection adopts a probability based on roulette wheel method. Adopting a heuristic crossover operator to ensure that the crossover offspring are likely to evolve towards the optimal solution. A mutation operator with adaptive strategy adjustment is proposed, which uses inverse trigonometric functions to appropriately adjust the mutation probability. Based on MATLAB simulation analysis, the number of iterations, planning time, and path time have all been significantly optimized.

2.3.3. Particle Swarm Optimization

Particle Swarm Optimization (PSO) was proposed by Eberhart et al. in 1995 [35]. Its core idea is that each individual in a group continuously changes their search pattern based on their own experience and the experience of other individuals. Each individual (particle) only has two attributes: position and velocity. The particle swarm optimization has strong robustness [36].

Wu Nini et al. proposed a path planning method based on autonomous learning particle swarm algorithm to reduce the path length of mobile robots [37]. Establish a path planning model with the shortest path as the optimization objective. Use obstacle expansion method to prevent collision of robots. A learning strategy pool composed of multiple particle-learning strategies is introduced, enabling particles to have autonomous learning ability. Through the algorithm performance test, the improved algorithm has stronger optimization ability and greater stability. Zhao Di et al. proposed an exchanging PSO (EXPSO) algorithm based on global and local information exchange during search [38]. A new exchange item is added for the local information and global information in the particle search process. Use the penalty function to avoid obstacles. Smooth the path using cubic spline function. The simulation results show that the speed and convergence precision of the EXPSO algorithm in searching for the global optimal solution have been optimized. Hao Kun et al. proposed a path planning method based on region search-adaptive particle swarm optimization algorithm (RS-APSO) [39]. The regional search algorithm is used to solve the problem of long exploration time and reduce invalid information in the map. Two variable operators are proposed to adjust the inertia weight factor and improve the acceleration factor adaptively. Finally, a new dynamic obstacle avoidance strategy is proposed to ensure the safety of robots. The simulation results show that the RS-APSO algorithm has stronger optimization capabilities in static environments and can successfully generate safe path in dynamic environments.

3. Conclusion

This article briefly introduces the basic principles of each path planning algorithm involved, and summarizes the research progress of relatively new improved algorithms. The selection of literature is based on different types of mobile robots, such as AGV, mining mobile robot, UAV, etc. The improved algorithms in the literature put forward different improvement measures for the defects of the original algorithm. The simulation and experiments results show that compared with the original algorithm, these improved algorithms have different degrees of improvement and optimization. From the perspective of current development status and practical needs, research on path planning algorithms for mobile robot in the future should focus more on the following aspects.

Most existing research is based on simulation environments using software such as MATLAB, Webots and ROS. However, the complexity of practical environments is often determined by different factors, such as spatial irregularity and disorder. The actual dynamic factors such as lighting, weather, temperature, and other environmental changes can also affect the final effectiveness of the algorithm. When encountering unexpected scenarios, the accuracy and security of the path cannot be guaranteed. Therefore, future research on improving algorithms should focus more on enhancing their adaptability and intelligence. To obtain the optimal path by making autonomous adjustments to complex and variable environments.

Different algorithms have their own advantages and disadvantages. A single path planning algorithm cannot meet the complexity of current practical application scenarios. People often require path planning algorithms that meet a combination of high efficiency, safety, and low consumption requirements. Introducing corresponding optimization algorithms at different stages of path planning can solve corresponding problems. This can effectively improve the reliability and practicality of path planning.

Most existing improvements are modifications to the algorithm function itself. In addition, it can cooperate with technologies of other disciplines. For example, multi-sensor information and data fusion can provide more detailed data of mobile robots. Combined with control strategy and stability analysis technology in control engineering, the efficiency and performance of path planning algorithm can be improved. Through the coordinated control strategy, the cooperative operation of obstacle avoidance and path optimization among multiple robots can be realized. To sum up, technology integration with other disciplines can further improve the practical feasibility of the path planning.

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