

Applications and Prospects of APF in Robot Path Planning

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Abstract. Path planning is important to realize intelligent and automatic unmanned systems. The artificial potential field (APF) method has attracted wide attention because of its brief and elegant algorithm. However, the APF method often appears to have the local minimum value in the actual working process, which leads to the failure of planning feasible routes and navigation failure. This paper discusses and summarizes the application of the APF method in different fields, including mobile robots, unmanned vehicles, robotic arms, unmanned aerial vehicles, and underwater unmanned vehicles. At the same time, many feasible methods to solve the local minimum problem and advance path-planning efficiency are introduced. The purpose of this article is to give practitioners who are new to path planning a basic understanding of its application scope and to gain a basic understanding of the principles, advantages, and disadvantages of the APF algorithm. The importance of this study is to summarize the application of the APF method in different fields of path planning and its combination with other algorithms. It helps beginners understand the APF algorithm more comprehensively.

Keywords: Path planning, APF, Robotics.

1. Introduction

Mobile robot technology is in a stage of rapid development. With the advancement of artificial intelligence, sensors, and automatic control technology, robots have stronger autonomy and perception capabilities and can make decisions and navigate independently in complex and dynamic environments. At present, mobile robots have been widely used in fields such as logistics and distribution, agricultural automation, intelligent manufacturing, medical services, and security inspections, making significant contributions to efficiency improvement and cost optimization in various industries. In the process of performing navigation tasks, robots often need to implement the following functions: environment modeling and positioning themselves in the environment, motion control, obstacle detection, and avoidance, and the ability to move in dynamic environments. The four key aspects of navigation challenges are perception, localization, motion control, and path planning [1].

Among these challenges, path planning is arguably one of the most critical aspects of the navigation process. Path planning is to determine a collision-free route in a specified environment. But usually in the working environment of automatic mobile robots, multiple paths exist between the departure point and the final point. The determination of path to be followed (the optimal path) is often determined by constraints and conditions, such as the distance between the initial point and the terminus. The shortest path, or the shortest travel time without collision. Excellent path-planning algorithms can make automatic mobile robots capable of many complex tasks: when driving, the vehicle can avoid collisions in the shortest possible time [2]. In underwater exploration, due to the energy of autonomous underwater vehicles, Resources are limited, and energy needs to be considered as an important factor in route planning to achieve safe autonomous navigation [3].

Since the 1970s, path planning has attracted the attention of many researchers. Path planning is typically categorized into global and local path planning. Global path planning is most effective in static environments where comprehensive knowledge of the surroundings is accessible. When the environment is unknown or dynamic, local path planning is often preferred. After years of research, many path-planning algorithms have also been proposed. Dijkstra's algorithm solves sub-problems by calculating the shortest path from the source to the nearest vertex [4]. A* employs a similar strategy

but focuses the search on the most promising states, which can significantly reduce computation time [5]. To generate paths that can avoid collision, the D* (Dynamic A*) algorithm is utilized. The RRT algorithm will be extended to all areas and will be assigned to each node according to the weights, creating a path from the starting point to the goal, etc. This article primarily focuses on the principles and applications of the APF method related to path-planning problems. The solutions to local minimums that may be encountered in APF methods are summarized. And look forward to the future development of the APF algorithm.

2. Theoretical background of APF

2.1. Principle of APF

The core principle of the APF method involves creating an artificial potential field within the robot's operating environment. In this working environment, the target position as an attractive pole exerts an attractive force on the robot, the obstacle as a repulsive pole exerts a repulsive force on the robot, and the resulting path is output as a result [6]. The APF method was first proposed by Khatib in 1986 for robotic arm motion and obstacle avoidance control of mobile robots. Formulas 1 and 2 are traditional repulsive force formulas.

$$U_{x_d}(x) = 1/2k_p(x - x_d)^2 \quad (1)$$

$$U_o(x) = \begin{cases} \frac{1}{2}\eta(\frac{1}{\xi} - \frac{1}{\xi_0})^2 & \text{if } \xi \leq \xi_0 \\ 0 & \text{if } \xi > \xi_0 \end{cases} \quad (2)$$

Where, x represents the coordinates of the robot position, x_d represents the coordinates of the target point, and k_p is the proportionality constant, η is the proportional constant, ξ_0 represents the limit influence distance of the barrier, and ξ represents the minimum distance from the mobile robot to the barrier [7]. The net force acting on the robot in the artificial potential field is:

$$U_{total} = U_{x_d} + \sum U_o. \quad (3)$$

2.2. Advantages and Limitations of APF

APF has received a lot of praise for the simplicity and elegance of its algorithm formula, and the simplicity of the algorithm makes it well-suited for solving dynamic environment problems while saving time for path planning problems. In the underwater navigation simulation test of autonomous underwater vehicles (AUV), when adopting the same obstacle limit influence distance, the model using the improved A* algorithm combined with APF has higher performance indexes than the model using only the improved A* algorithm. Among them, the number of nodes being evaluated is reduced by nearly 70% on average, and the calculation time is reduced by nearly 64% on average [2]. In another study combining the A* and APF methods, the integrated algorithms generate a path that can keep the AUV safely away from obstacles, making it safer than the result of using only the A* algorithm [8]. In known and unknown environmental path planning problems, compared with the conventional Q-Learning algorithm, the path length in online mode is reduced by 18.83%, the path smoothness in offline mode is increased by 169.75%, and the training time is reduced by 74.84% [9].

APF algorithm also has defects. In complex environments, it may get trapped in a local minimum, leading to the failure of path planning. In other words, when the force of multiple obstacles and target points on the mobile robot counteracts each other, the mobile robot will stop moving, resulting in path planning failure. This situation commonly arises when two obstacles are positioned close to each other in front of the mobile robot, with the target located on the opposite side, as illustrated in Fig. 1., the problem of impassability will occur. In this case, the resulting repulsion field will pull the mobile robot in the opposite direction to the target [10], so in practical applications, the APF method is often used in combination with other methods.

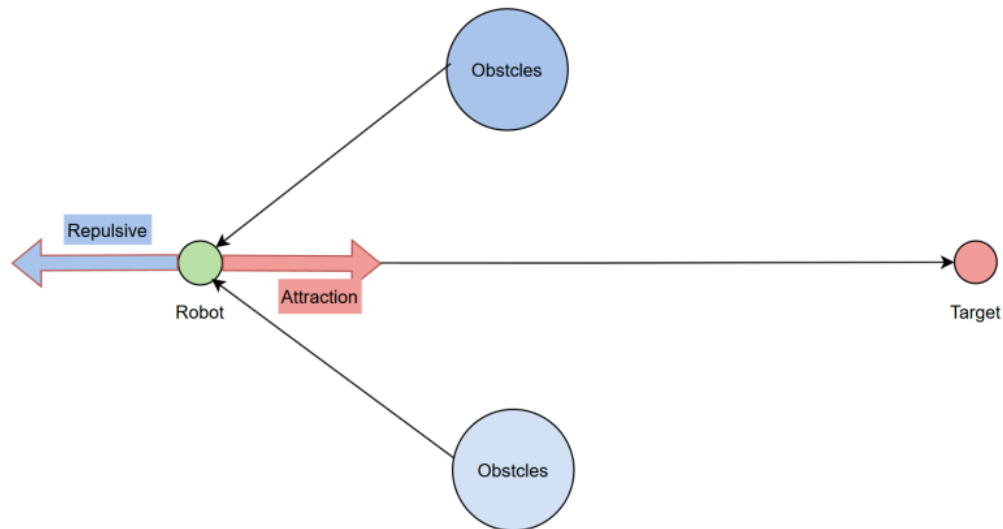


Fig. 1 Principle of local minimum problem in APF. (Picture credit: Original)

3. Applications of APF in Mobile Robots

3.1. Application Environment

Since the APF method was initially introduced in 1986, it has been widely used in many application directions of robot and vehicle autonomous navigation:

1). Autonomous robots and vehicles

Mobile robots: APFs are used for indoor and outdoor navigation of autonomous mobile robots, such as service robots in homes or hospitals, warehouse robots, or autonomous delivery drones.

Autonomous vehicles: APF helps to help the vehicle avoid obstacles while maintaining operation on a collision-free path, especially when the vehicle is traveling in a dynamic environment with pedestrians and other vehicles.

2). Manipulators and industrial robots

In industrial environments, robotic arms equipped with APF methods can safely navigate around obstacles and optimize tasks such as assembly or material handling, where accuracy is critical.

3). Unmanned Aerial Vehicle (UAV)

APF is used for path planning of UAVs for applications such as surveillance, delivery, and search and rescue missions. UAVs can use APF to avoid obstacles (trees, buildings) in 2D and 3D space.

4). Marine and underwater vehicles

APFs are used in Autonomous underwater vehicles (AUVs) to navigate through complex underwater terrain, avoid obstacles such as coral reefs or seabed while performing tasks such as underwater exploration, inspection, or search and rescue, or simultaneously meet other goals such as energy conservation.

3.2. Typical Application Cases of APF

3.2.1. Autonomous Mobile Robots and Mobile Vehicles

Autonomous mobile robots have been widely used in storage, logistics, and other fields as shown in Fig. 2. In the process of autonomous navigation, in order to improve work efficiency and reduce energy cost, reducing redundant nodes and improving the smoothness of the planned route is crucial. APF can be combined with other algorithms to improve the performance of path-planning algorithms. In the simulation experiment of mobile robot obstacle avoidance, GAO et al. combined the A* algorithm with the APF algorithm improved by the simulated annealing algorithm (CSA-APF) [11]. By simulating the temperature change in the process of annealing, the SA algorithm searches for new

solutions with different randomness and finally converges to the global optimal solution to avoid the occurrence of locally optimal solutions. The simulation results illustrate the CSA-APF algorithm makes the robot path planning can be completed successfully, and compared with the traditional APF algorithm, the path search time is shortened by 44.86%. Compared with the results obtained by the A* algorithm, the path turning point is reduced, and the path length is reduced by nearly 6% [11]. Orozco-Rosas et al. proposed the memEAPF algorithm that combines membrane computing (cell-like P systems), evolutionary computing (specifically, a genetic algorithm) and APF methods. The simulation results show that the memEAPF algorithm can obtain the path planning solution in a short time matter in the static environment or the dynamic environment [12].



Fig. 2 Application of mobile robots in factory [13]

Unmanned autonomous vehicles are the hotspots of the current development of science and technology. The route planned by unmanned vehicles can meet the safety and comfort of passengers when driving quickly is one of the core issues of unmanned vehicle technology. In a study conducted by Huang et al., an APF method was combined with the resistance network, and the acceleration constraint of the vehicle was added to meet the comfort requirement. The simulation results show that the system can make the unmanned vehicle maintain the optimal speed at the same time. React effectively to obstacles to avoid collisions [14]. Chen et al. enhanced the APF method by incorporating a velocity repulsive field, an obstacle position repulsive field, and a road boundary repulsive field., and processed the cumulative resultant force vector experienced by autonomous vehicles as a whole, so as to ensure that the autonomous vehicle fleet can safely avoid obstacles and maintain a consistent speed in the overtaking process [15].

3.2.2. Manipulators and Industrial Robot

As shown in Fig. 3, manipulators are extensively utilized in industrial manufacturing. The path-planning of the manipulator plays a significant role in the safety of industrial production. Path planning can improve the safety of the manipulator. It avoids the collision between the manipulator and the surrounding environment during the movement and protects the safety of the equipment and the operator. At the same time, good path planning is also beneficial to reduce the energy consumption of the manipulator, extend its service life, and reduce maintenance costs. Barrier avoidance path-planning of a manipulator refers to its search for a collision-free route in the working environment. Due to the hinged connections between the joints of the manipulator, path planning must account not only for the movement of the manipulator's end-effector but also for the motion patterns of each joint. APF method is extensively utilized for its elegant model, excellent real-time performance, high

algorithm efficiency, as well as smooth generated path. However, it is prone to getting trapped in local minima, preventing the manipulator from continuing its movement [16]. According to Zhao et al., recognizing obstacles as regular geometries in their modeling can speed up the computation of path planning. In addition, on the basis of the traditional APF, virtual obstacles are added and the attraction coefficient of the target joints are increased. The improved APF method avoids the local minimum problem and makes the planned path smoother [17].



Fig. 3 Manipulator for industrial use [18]

3.2.3. UAV

UAVs were firstly introduced to the military in the 20th century by the 21st century, they have become an important asset to most militaries around the world. Today, in addition to military applications, UAVs are also widely used by civilians, for business, entertainment, and other fields, as shown in Fig. 4. Jayaweera and Hanoun proposed the dynamic APF method (D-APF). The force function of D-APF not only considers the relative position of the target and the UAV but also considers the relative velocity. This design allows the UAV to respond to the acceleration or deceleration of the target, so as to better follow the dynamic changes of the target. In addition, D-APF uses an exponential attraction and repulsion function, which means that when approaching the target, the attraction and repulsion will change rapidly, thus helping the UAV to quickly follow the moving target. This allows the UAV to respond more flexibly to target speed changes and direction shifts. In addition, D-APF is more comprehensive in avoiding obstacles in 3D space, and it generates repulsive forces not only in the horizontal direction but also in the vertical direction. Especially when facing tall obstacles (such as bridges, and trees), the UAV can avoid the obstacles by changing its height without having to rely only on horizontal displacement. Results of the simulation show that, compared with the existing general APF method, the D-APF method requires less computing power, has higher stability, the lowest overshoot, the shortest stabilization time, and is more effective in responding to sudden changes in target speed or direction. Such features indicate that the D-APF method is more matching for the path-planning of UAV tracking ground moving targets in the environment with obstacles [19]. According to the research of Huang et al., the parallel search algorithm and APF algorithm are combined to solve the local minimum problem that traditional APF algorithms may encounter. When the UAV encounters an unreachable target, it will not only bypass the nearest obstacle but also detect the obstacle between the current point and the goal point simultaneously. If there is no overlap between the obstacle and the target point, the UAV can move directly to the target. Otherwise, it will choose a feasible path to bypass the obstacles and efficiently reach the target. The improved APF method generates a shorter path with less time consumption so that the UAV can reach the target in a more efficient way in a complex environment, saving flight time and energy [20].



Fig. 4 Civilian UAV [21]

3.2.4. Autonomous Underwater Vehicles

The development of autonomous underwater vehicles (AUV) began in the middle of the 20th century, and it was mainly used in the military field in the early stages, such as reconnaissance, mine-laying, and other tasks. With the continuous progress of technology, the application of AUV in the civil field has gradually expanded, including Marine scientific research in Fig. 5, seabed resource exploration, underwater engineering detection, and so on. A good path planning algorithm plays an important role in AUV, which can improve mission efficiency, ensure navigation safety, and optimize the allocation of energy and computing power. Zhang et al. integrated the APF algorithm with the A* algorithm. By incorporating APF, the algorithm could quickly acquire obstacle information in the process of iteration and reulate the direction of path-planning based on the virtual force, thereby reducing the number of potential nodes and enhancing overall efficiency [2]. According to a research of Chen et al., an optimization scheme of enhanced Artificial Potential Field ant Colony algorithm (APF-AC) was proposed. Experiment results are shown in Table 1. The enhanced APF-AC algorithm achieved a reduction in path lengths by 1.57% and 0.63% in simple environments, and by 8.92% and 3.46% in more complex environments. In terms of iteration time, it was reduced by approximately 28.48% and 18.05% in simple environments, while complex environments saw reductions of 18.53% and 9.24%. Furthermore, testing on the AUV platform confirmed that the experimental results were consistent with the simulations. This improved method not only decreases computation time but also minimizes energy consumption, while maintaining a high level of safety for AUVs [22].

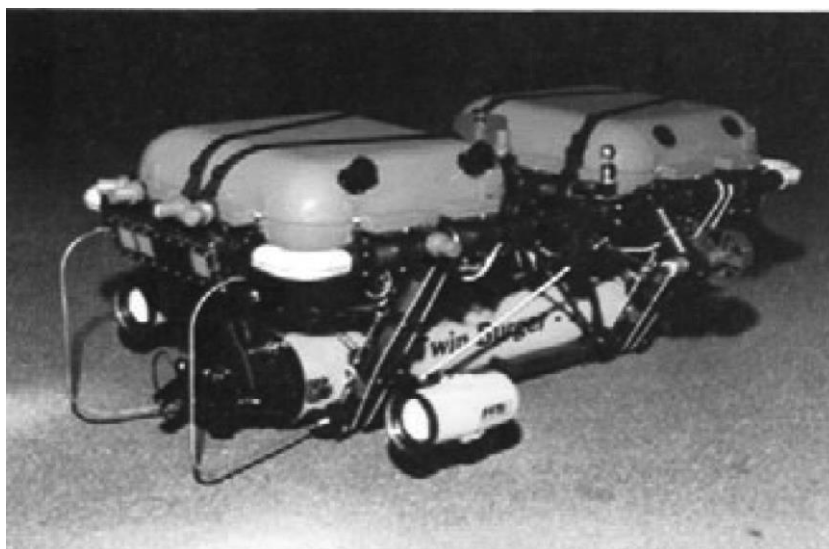


Fig. 5 Twin-Burger 2 Autonomous Underwater Vehicles [23]

Table 1. Comparison of data related to experimental [19]

Index(Average)	iteration		Path length	
	Simple environment	Complex environment	Simple environment	Simple environment
Traditional ant colony algorithm	42.6	106.7	30.63	49.635
Improved APF-AC algorithm	8.3	41.4	30.15	45.21

4. Conclusion

As one of the important application directions of robotics, path planning plays a vital role in intelligent systems. It can not only improve the working efficiency of the system, optimize the resource allocation of the intelligent system, but also escort the security of the intelligent system. With the rapid development of autonomous technologies in recent years, path planning has garnered widespread attention from researchers, particularly for its potential to enhance the capabilities of intelligent systems.

This article mainly introduces the improvement and innovation of the APF algorithm in several application directions of path planning. Specifically, areas including autonomous mobile robots, mobile vehicles, manipulators, UAVs, and AUVs are summarized. In each part, the overall performance of the improved APF algorithm is compared with that of the traditional algorithm, and the results are better than those of the traditional APF algorithm. At the same time, different methods to solve the local minimum problem that may be encountered in the APF algorithm are sorted out, including the combination of parallel search algorithm and adding virtual obstacles.

This paper provides a comprehensive understanding of the APF algorithm and its various applications across different systems. The purpose is to provide not only an introduction to the algorithm but also insights into its comparative advantages in different fields. Looking forward, one of the critical focuses in future research will be on how to more effectively address the local minimum problem inherent in the APF algorithm. The exploration of new strategies and combinations of techniques to overcome this challenge will be a central theme in the continued evolution of APF-based path-planning algorithms. By enhancing the algorithm's capacity to navigate intricate environments and avoid being ensnared in local minima, future developments will lead to the creation of even more advanced and efficient intelligent systems.

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