The Research Progress of Path Planning Algorithms

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Abstract. At present, path-planning for mobile robots is a hot problem. In the previous scientific research, A*, Dijkstra, rapidly-exploring random tree (RRT) and many other algorithms have appeared. To provide a clearer understanding of these algorithms, this article organized the idea and development of Q-learning, A* algorithm, ant colony algorithm, RRT algorithm and Dijkstra algorithm. According to the time order, this article researched several applications of the five algorithms respectively. Besides, optimization of the five algorithms in the past few years were listed. There are also examples of combined algorithms, which have better efficiency compared to using one algorithm alone. By analyzing the five algorithm and their optimization, the common problem and solution was found. The common problem of these algorithms is that a shorter and smoother path needs to be solved and the convergence speed needs accelerating. At present, the main solution can be divided into two aspects. One is to improve the algorithm itself, and the other is to combine different algorithms. In the future, more kinds of combined algorithms will emerge, and a better solution of path planning can be obtained to improve efficiency and reduce energy cost.

Keywords: Q-learning, A* algorithm, ant colony algorithm, RRT algorithm, Dijkstra algorithm.

1. Introduction

Nowadays, there is a growing trend that mobile robots are assisting human in more and more fields, like industrialization, transportation and modern agriculture. First, industrial robots with advanced path-planning algorithm can complete lots of work in factories. For example, robot arms with wolf pack algorithm can precisely do the welding work [1]. Less errors could exist and more people can be relieved from the hardship of welding. Thus, a great deal of material resources and manpower could be saved. Meanwhile, mass production and good quality of products can be guaranteed. Moreover, industrial robots with different kinds of path-planning algorithms can tailor the products according to customer's needs. Second, a giant revolution is happening in transportation, which is mainly concerned with unmanned vehicles. Q-learning, A* and Dijkstra algorithm have all been applied to unmanned cars and some modifications have been made to improve the safety and efficiency [2,3]. Besides, the path-planning algorithms have many advantages compared with manpower, especially in complex and dangerous environment. Therefore, these algorithms are also used in unmanned ships, coal mining and city planning [4-7]. Third, path-planning algorithms have wide application in agriculture. In the past few years, intelligent agriculture has emerged. The goal of intelligent agriculture is to build a modern and green agricultural system. Within this system, vehicles, ships, drone swarms, and satellites all play an important part. To run the system smoothly, path-planning is the key point.

With the development of mobile robot, great importance has been attached to the path planning process. Path planning is vital because it enables robots to behave like a real creature on the earth. Ants can find the location of food based on legacy pheromone approach. Birds can migrate from one continent to another because of the navigation system in its body. These are common phenomenon in the natural world. Inspired by the behavior of the creatures, scientists developed bio-inspired algorithms for path planning process. In this process, the search of the optimal path is a hot problem. The optimal path is commonly recognized as a smooth curve from the start point to the terminal point. However, working out the smooth curve is challenging. Nowadays, robots can feel the outside world through diverse kind of sensors, like the vision camera and lidars. After robots receive data from the sensors, they convert the data into quantities of nodes. However, the nodes are discrete. Thus, a theory is needed for linking the nodes and forming a path and the theory leads to different algorithms.

Path planning algorithms can be approximately categorized into four types, which are respectively fuzzy logic, SLAM, reinforcement learning and intelligent optimization [8].

The idea of fuzzy logic algorithm is to build a database of behavior rule, which can be applied in diverse situations [8]. When the robot plans its route in an unknown environment, it decides where to go by using the database.

SLAM was proposed by Smith and Cheeseman in 1986 [8]. Via acquiring external data, SLAM can deduce the motion model and observation model. Then, the robot can attain a real-time estimation of the motion state. With the feedback information from sensors taken into account, SLAM can be used widely in practical applications [8]. SLAM is fully developed compared with other three types. Thus, fewer optimizations can be made.

The core of reinforcement learning is that the maximum cumulative reward should be obtained. At each node in a map, the robot chooses the step with maximum reward and the optimal path can be found eventually.

The intelligent optimization algorithm is a bio-inspired algorithm, including ant colony algorithm, genetic algorithm, immune algorithm etc. Through many iterations during its procedure, this kind of algorithm endows robots with excellent ability of optimization.

2. Q-Learning Algorithm

The Q-learning algorithm was initiated by Watkins in 1989. It is categorized as a kind of reinforcement learning [9]. It keeps searching for the action which produces the largest reward and eventually find the shortest path. Thus, what the Q-learning does can be concluded as trial and error. There is one specialty about this algorithm. The problem which it can solve must have Markov Property, because Q-learning is based on the theory of Markov Decision Process [9].

There are three predominant things in Q-learning: the Raster graph, the code and Q-table. First, the Raster graph is seen as the simulation of the environment. It serves as a map. Different blocks in the graph represent different objects, such as obstacles and space. Second, the code is a way to achieve the goal of this formula [9]:

$$Q(s,a)\leftarrow Q(s,a)+\alpha[r+\gamma \text{argmax}_{a'}Q(s',a')-Q(s,a)] \quad (1)$$

The formula represents the idea of Q-learning. To explain the formula, there are five technical words: state, action, reward, policy and model-free/model-based. The state means how the robot is behaving, like its speed or the direction that it is facing. The action is what the robot can choose to do at every point. The reward is what the robot can attain after choosing the action. If the robot chooses to approach an obstacle block in the Raster graph, the reward could be a negative number. However, if the robot's choice is to reach a space block, the reward can be a positive number. The policy is the choice of the robot at every time point. Model-based suggests that the state transition probability is known and the probability of each choice is known. On the contrary, model-free means that state transition probability is unknown. α is the learning rate ranging from 0 to 1. When α is large, Q-learning algorithm tends to explore other optimal path. When α is small, Q-learning prefers to implement the optimal path which is already known. Third, after running the Q-learning algorithm, a Q-table is obtained. In each block of the raster graph, the reward number is shown. As a result, the optimal path is found.

After decades of development, the Q-learning algorithm is applied in diverse fields. In 2018, XiaoMeng Liu optimized the Q-learning method and brought forward a Q-learning algorithm based on layered epsilon greedy algorithm. He adhibited it into path-planning process of unmanned cars and significantly improved the study speed and environment adaptability of unmanned cars [2]. Also in 2018, Sadhu, A. K and his group proposed an algorithm named Q-learning induced firefly algorithm (QFA). QFA is a combination of Q-learning and Firefly Algorithm. It assists in the path planning process of robot arm [10]. In 2020, Zhao, M., Lu, H., Yang, S., and Guo, F. initiated an Experience-Memory Q-Learning (EMQL) algorithm [8]. EMQL can reduce the convergence time

and length of path [8]. In 2022, MingFan Gong and his group advanced an improved Q-learning algorithm and applied it to the voyage of smart ships [5]. This improved Q-learning added angular information in the two-dimensional location information [5]. Besides, the reward function was optimized, with the information of heading and obstacle included [5]. The algorithm was an advance in path-planning field because it solved the problem of singleness of reward function [5]. Plus, it helps cut the energy consumption of smart ships [5].

3. A* Algorithm

A* algorithm is a tributary of path-planning algorithm. It is a kind of Heuristic path search [11]. To understand its theory, five technical words should be introduced: the Search Area, Open List, parent, Heuristics Function, Manhattan Distance. The Search Area is divided into double dimensional array, and each of the array element corresponds with one small square. The Open List functions as the storage of the node to be detected. The node that has been detected is stored in the Close List. Parent is the node which is used for backtracking. Heuristics Function is used for exploration. Before the optimal path is found, the robot cannot foresee what obstacle could appear. Thus, Heuristics Function can help decide where to go based on the actual environment. Manhattan Distance is the total length of the distance travelled.

A* algorithm can rapidly get the target lock through the evaluation function [11]. The evaluation resembles this function [4]:

$$f(n)=g(n)+h(n) \tag{2}$$

f(n) is the valuation function [11]. It represents the overall generation value from node n to the terminal point [11]. g(n) is the actual generation value from the start point to node n [11]. h(n) is the Heuristics Function [11].

In the previous researches, A* algorithm has the advantage that it can execute fast and plan the shortest path [11]. However, the path planned by conventional A* algorithm has many twists and low smoothness [4]. Besides, some parts of the path do not have a safe distance from the obstacle [4]. Thus, most researches combine other algorithms and methods with A* algorithm to solve these problems. In 2022, ZeGuang Ying and Qi He put forward a new idea of combining A* algorithm with Floyd algorithm [4]. By adding the Floyd algorithm, redundant node were left out [4]. Therefore, a path with higher smoothness and less twists was achieved [4]. In addition, they optimized the raster graph by setting the safe distance and adding obstacle impact factor [4]. Their result was successfully applied in path-planning process of unmanned boats [4]. Also in 2022, Xu Li and his team proposed a different approach of optimizing A* algorithm [11]. They combined fuzzy algorithm and fractal dimension method with A* algorithm and improved the robustness of the algorithm [11].

A* algorithm is a dynamic method in recent years, and it has been used in various fields. In 2018, Hou, K. and his team applied A* algorithm in unmanned surface vehicle [3]. Through experiments and analysis, they realized both effective and efficient movement of Unmanned Surface Vehicle (USV) [3].

In 2020, Li, M., and Zhang, H. used A* algorithm to realize the path-planning of autonomous under water vehicle in a three-dimensional environment [12]. They compared A* algorithm with Dijkstra algorithm and the results indicated that A* algorithm showed better real-time performance and had higher efficiency [12].

4. Ant Colony Algorithm

Ant colony algorithm(AGA) is classified as a bio-inspired algorithm. It is initially proposed by M. Dotigo in 1996 [13]. This algorithm is an analog of the ants' behavior. When the ants hunt for food, they adopt an approach as legacy pheromone [14]. The ants leave pheromone on the path they pass by [13]. The path with a higher concentration of pheromone has a higher probability to be chosen [13]. Thus, the simulation uses this approach and Heuristic function to decide which direction the

ants move towards [14]. Traditional ant colony algorithm uses roulette method to de cide where to go [14]. The decision is based on the probability of choosing adjacent grids. The traditional ant colony algorithm has the transfer probability formula as follows [13]:

$$P_k(i,j) = \begin{cases} \frac{\tau^{\alpha}(i,j)\eta^{\beta}(i,j)}{\sum \tau^{\alpha}\eta^{\beta}} & j \in J_k(i) \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

In this formula, α stands for pheromone heuristic factor and β stands for expectation heuristic factor [13]. $J_k(i)$ represents the steps available for ant k to choose [13]. $\tau^{\alpha}(i,j)$ is the concentration of pheromone on path L(i,j) [13]. $\eta^{\beta}(i,j)$ is the reciprocal of the distance between two nodes [13]. Each time all the ants finish their travel, the concentration of pheromone on every path updates [13].

Traditional ant colony algorithm has the demerit that it has a slow convergence speed. Also, it is easy for the algorithm to fall into local optimum. In order to settle the problems, in 2016, Liu, K and Zhang, MX combined annealing algorithm with AGA [6]. Their results provided a solution to local optimal [6]. In 2022, Ping Qian and his team brought forward a new idea [13]. Their team optimized the initial concentration of pheromone and the updating means of pheromone to improve the convergence speed [13]. Besides, they combined AGA with Genetic Algorithm to create ACAGA algorithm [13]. Thus, the problem of local optimal is solved [13]. Also in 2022, Yi Ke proposed an approach to combine the ant colony algorithm with Q-learning [9]. This theory can reach a higher level of solution accuracy, especially in complex environments [9].

In the past few years, ant colony algorithm has been applied in several fields. In 2016, Liu, K and Zhang, MX syncretized annealing algorithm and ant colony algorithm [6]. Their results were successfully applied in coal mining [6]. In 2022, Yi Ke used the combination of reinforcement learning and ant colony algorithm to plan the path for robots [9]. His results showed that the combined algorithm had a more splendid precision of path-planning compared with using the two algorithms separately [9]. Also in 2022, Ping Qian and his team improved ant colony algorithm and used it in path-planning process of underwater robots [13]. In 2023, YueFei Wu and his team made a melioration of ant colony algorithm and applied it in mountain rescue [14]. This research is of paramount importance because it shortens the rescue time. It gives people hope when they are trapped in mountain areas with poor infrastructure.

5. Rapidly-Exploring Random Tree (RRT) Algorithm

RRT algorithm is a kind of path-planning algorithm based on sampling [15]. RRT scales randomly in a global environment [15]. With a fixed step size, the rapid-exploring trees grow. Until the trees reach the goal point without colliding with the obstacles, the growth of the trees can stop. RRT has the benefit of strong path search capability in a high-dimensional environment [15]. However, it spends too much time on path-planning process. Plus, the search method of RRT brings quantities of redundant work in a global environment.

The solution of finding optimal path is of great challenge. In 1998, LaValle brought forward RRTs [16]. From then on, a large number of RRT-variants appeared. In 2000, Kuffner and LaValle came up with RRT-connect. RRT-connect uses a double tree method, where one growing from start point and another from the terminal point [16]. Sadly, the scale of the trees is not controlled and optimality cannot be assured [15]. Then, in 2011, Karman and Frazzoli proposed RRT* algorithm [16]. Optimisation modules, along with the ChooseParent and Rewire procedures were added in RRT* algorithm [16]. Therefore, RRT* has the asymptotic optimality [17]. RRT* is a giant leap in the developing process of RRT.

In addition to searching for the optimal path, shortening the convergence time is also a vital task. RRT*-Smart explains an in intelligent method of sampling, but it is hard to run the algorithm in a computer system with limited memory [16]. To break this limit, RRT*FN was proposed [16]. To further accelerate convergence speed, P-RRT* was put forward in 2016 and Quick-RRT* emerged in 2019 [16].

In recent years, more advanced methods of RRT have come forth. In 2020,Yanjie Li and his team proposed PQ-RRT* and applied it in path-planning process of mobile robots [16]. PQ-RRT* syncretizes the strength of P-RRT* and Q-RRT* [16]. PQ-RRT* significantly reduces the convergence time [16]. In 2022, HaoDuo Jia and his team proposed a theory of syncretizing artificial potential field and Informed-RRT* [15]. This theory can perform path optimization iterations efficiently by accelerating the planning speed and shortening the length of optimal path [15]. In 2023, Wei Zhen and his team also combined Informed-RRT* and artificial potential field to plan path for mobile robots. They brought forward a solution to path-planning problem in a dynamic environment [17]. The path planned by this method turns out to be shorter and smoother.

6. Dijkstra Algorithm

Dijkstra algorithm is a method on the basis of grid. The n×n grid is used to simulate the area of exploration [18]. Every cell in a grid can represent the presence or absence of barriers. In addition, Dijkstra algorithm is a sort of greedy algorithm [19]. During its searching process, it perceives the start point as the central origin. Then it drills down its search until it finds the shortest path from central origin to every node [19].

The advantage of Dijkstra is that the algorithm is convenient and simple [19]. Besides, the global optimal path can be attained precisely using Dijkstra algorithm. However, it is inevitable that redundant nodes can appear, which results in low efficiency. To settle these problems, in 2021, QuanYong Li and his team introduced path smoothness based on Dijkstra algorithm, and reduced the running time of robots [19]. Nevertheless, there are still redundant nodes. Also in 2021, Zhang and his team proposed a new heuristic function combined with artificial potential field and applied it in unmanned surface vehicles [19]. However, they did not take actual turning radius into consideration. In the same year, Luan and his team syncretized Cubic Bezier curve with hybrid genetic algorithm to provide smooth path for mobile robots. This theory also has demerit when the robot is too close to the obstacles [19]. In 2022, Hui Gong along with the teammates proposed an algorithm combining geometry topology with Dijkstra algorithm. Their method can reduce the turning angle, thus improving the path smoothness. The running time was reduced as well [19].

D* algorithm also have widespread use in other fields. In 2022, Li Hui, Tong Pei and Zhang Xu brought forward a new method of determining the location for highway passenger transportation hubs by D* [7]. Their results can help improve transportation convenience and boost regional economy growth. Dijkstra algorithm also assists human in dealing with Covid-19. In 2023, Jason and his team used Dijkstra algorithm to find a nearest vaccine location [20]. Their results can help citizens save time to get vaccinated. Thus, more people are protected from the virus.

7. Conclusion

In this article, five different path planning algorithms were introduced, which are respectively Q-learning, A* algorithm, ant colony algorithm, RRT algorithm and Dijkstra algorithm. For Q-learning method, optimizing the reward function was a vital path to improve efficiency. The optimized algorithm of EMQL and QFA were introduced, along with several improvements. Q-learning was applied in unmanned vehicles and smart ships, also used in robot arms. For A* algorithm, it can plan out a short path quickly, but twists and low smoothness are inevitable. This article introduced two ways of optimization and its application in smart ships, unmanned cars and AUV underwater path planning. For ant colony algorithm, it rarely falls into local optimal, but its convergence speed is slow. It can be combined with other algorithms to overcome the demerits. ACA performs well in complex environments and can be used in mountain rescue and coal mining. For RRT algorithm, PQ-RRT* was introduced. Last but not least, Dijkstra algorithm was raised and several improvements were introduced.

From these five algorithms, A* has a wider application and can quickly solve a path planning problem. Q-learning have become popular in recent years with the development of reinforcement learning. The common problem of these algorithms is that the convergence speed needs accelerating and a more smooth and shorter path needs to be solved. The combination of different algorithms is a main solution at present. In the future, more kinds of combined algorithms will emerge, and a better solution of path planning can be obtained to improve efficiency and reduce energy cost.

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