Review of Path Planning Algorithms for Unmanned Vehicles

Yunyi Shen, Jian Liu, Yasong Luo
College of Weapon Engineering, Naval University of Engineering, Wuhan, China
syy19954321@163.com, 624535486@qq.com
Corresponding Author: Yunyi Shen Email: syy19954321@163.com

Abstract—**The knowledge of unmanned vehicles path planning algorithm is introduced. Firstly, the basic concept and steps of path planning are described. Secondly, it introduces Dijkstra algorithm, A-Star algorithm, RRT algorithm, PRM algorithm and other typical path planning algorithms from the classification ideas of the path planning algorithm based on search and sampling. The advantages and disadvantages of each algorithm are analyzed, and the applicable environment and conditions of the algorithm are summarized. Finally, several new algorithms and their development directions are introduced.**

Keywords—unmanned vehicle; global path planning; local path planning; algorithm

I. INTRODUCTION

In recent years, with the development of artificial intelligence, unmanned system technology has made great progress. In terms of intelligent transportation systems, Meituan and Baidu plan to take the lead in testing unmanned food delivery in Xiong'an in April 2018 to improve efficiency. In October 2020, China's first 5G unmanned bus with regular operation deployed by China Mobile and Qcraft Company was put into operation in Suzhou's high-speed railway New City to solve the problem of low efficiency of daily commuting. In the military sector, the Ukraine-made "Camel 4X4 UGV" successfully passed a series of test qualification tests in December 2020. The vehicle is designed to perform reconnaissance, destruction, cargo and escort missions, and can also be used to evacuate injured military personnel. In June 2021, the fourth "Rough Tooth Saw M5" unmanned tracked ground fighting vehicle entered service with the U.S. Army. The vehicle has durability and revolutionary capabilities, with a hybrid engine that enables quiet mobility and improved reliability.

Civilian unmanned vehicles are generally used to solve problems such as public transportation, while military unmanned vehicles can independently or cooperatively complete reconnaissance, patrol, attack and transportation tasks similar to military unmanned aerial vehicles and unmanned boats. The purpose is to be able to safely drive on various roads or in the field environment and efficiently complete assigned tasks. Unmanned vehicle system can be divided into task decision-making subsystem, environment awareness subsystem, path planning subsystem, vehicle platform control subsystem and task execution subsystem. Path planning, also known as task planning or route planning [1], is one of the core technologies of unmanned vehicle.

II. BASIC CONCEPT

Path planning refers to finding the optimal or better collision free path from the starting point to the target point in an obstacle environment according to the known static or unknown dynamic environment information and certain evaluation criteria [2]. Unmanned vehicle path planning is generally divided into global path planning and local path planning [3-5].

Global path planning is static planning that uses known information to search the optimal global path without collision from the starting point to the target point when obstacle information is fully grasped [6]. Among them, the optimal can be the shortest time, the shortest distance or the lowest cost. When the environment changes, local path planning must be used to generate local driving paths or tracks of unmanned vehicles [7].

Local path planning is a dynamic planning that can safely avoid obstacles and track the desired local path under the guidance of the global path according to the real-time obtained environmental information and positioning information [6]. Fig. 1 shows the composition and relationship between path planning and motion control in the unmanned vehicle system. It can be seen that path planning plays an important role in connecting the preceding and the following in the unmanned vehicle system.

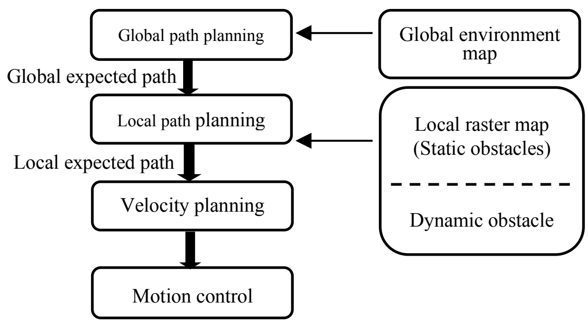

Fig. 1. Relationship of path planning modules

III. STEPS OF PATH PLANNING

The steps of unmanned vehicle path planning mainly include environment modeling, path search and path smoothing. Environment modeling is an important part of path planning. Path search is based on environment modeling to find a driving path according to the corresponding algorithm, and path smoothing will further process the path obtained by path search to make it a practical and feasible path [8].

A. Environmental Modeling

Environmental modeling abstracts the environmental information of real space into a mathematical model that can be processed by computers. Therefore, environmental modeling is the basis of path planning, and reasonable environmental modeling has an important impact on the final effect of path planning [9]. When path planning uses global environment map or real-time environment and positioning information to plan the path, and environmental information is transmitted by the sensing system, the path planning processor will fuse the information into the corresponding environment map [10] and display it on the computer. The environment map can abstractly and accurately represent the environmental information of the actual space.

At present, grid method and viewable method are commonly used in environment modeling [11]. Grid method divides the environmental map into a number of rectangular cells, as shown in Fig. 2. The actual environment is described by the characteristics of grids. The granularity of grids has a great impact on the accuracy and efficiency of environmental modeling. Viewable method can transform the path planning problem into the shortest distance problem in viewable by connecting the starting point and target point in the environment map without crossing the obstacle, as shown in Fig. 3. However, viewable method is relatively inefficient in more complex scenes.

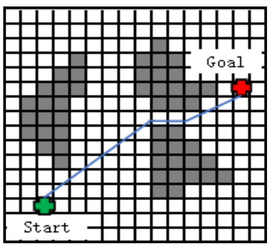

Fig. 2. Grid method

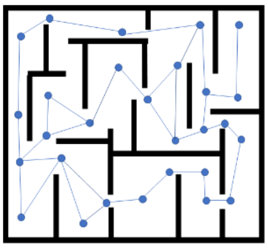

Fig. 3. Viewable method

B. Path Search

The path search problem of unmanned vehicles is mainly to find a feasible optimal or better path in complex environment based on environmental modeling from the search time, search efficiency, search energy consumption and other aspects by using corresponding algorithms [12]. Typical path planning algorithms mainly include Dijkstra algorithm, A-Star algorithm and its improved algorithm, RRT algorithm and PRM algorithm, which will be further introduced in the fourth part of this paper.

C. Path Smoothing

If the optimal or better path obtained by path search may not be a drivable path for unmanned vehicles, path smoothing is to optimize the path to make it a practical and feasible path. Literature [13] proposed a PRM path optimization method, which can reduce the number of path nodes and make the path smoother. In view of the smoothness and efficiency problems existing in current path planning methods, a path planning method combining smoothness and search efficiency was proposed based on JPS algorithm in literature [14], and trajectory optimization was carried out by using polynomials.

IV. COMMON ALGORITHMS AND CHARACTERISTICS

Path search needs to use the corresponding algorithm to find a feasible optimal or better path. For different path planning problems, different algorithms need to be used. Only by selecting the appropriate algorithm can path planning be carried out more efficiently and accurately. This part describes the classification ideas of path planning algorithms based on search and sampling.

A. Path Planning Algorithm Based on Search

The basic idea of search-based path planning algorithm is to discrete the state space into a search graph in a certain way and calculate its feasible solution with various heuristic search algorithms [15]. Common search-based path planning algorithms mainly include Dijkstra algorithm [16], A-Star algorithm [17].

1) Dijkstra algorithm

Dijkstra algorithm is a classical algorithm for solving shortest path problems. By selecting a node as the starting point, the path is gradually expanded outward from this point, and the nodes with smaller distance value are preferentially expanded until the path is extended to the end [18]. The algorithm process is shown in Fig. 4. As the algorithm traverses all nodes, it has a high success rate and good robustness. The disadvantage is that when the number of nodes is large, the search speed and efficiency will decrease.

In view of the low efficiency of the traditional Dijkstra algorithm, Literature [19] adopted MATLAB Robotic Toolbox to establish the model of planar robot operation arm according to D-H parameters, and used Monte Carlo point cloud to establish obstacle avoidance workspace and carry out path planning in point cloud space. An improved Dijkstra algorithm with small space occupancy, short path planning and high search efficiency is obtained.

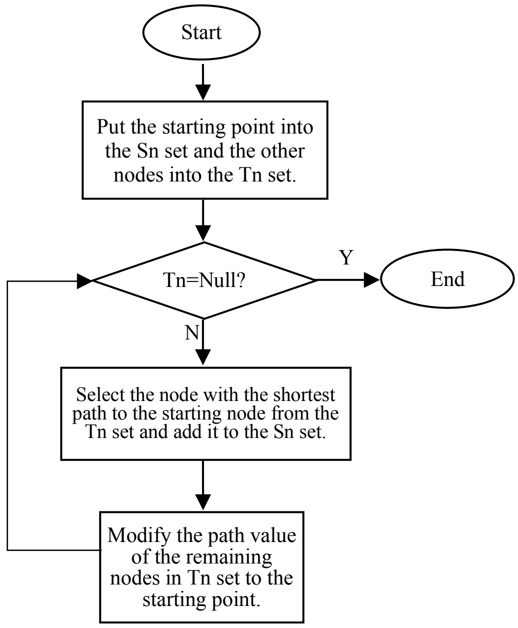

Fig. 4. Dijkstra algorithm flow chart

2) A-Star algorithm and improvement

A-Star algorithm is a fast and effective heuristic search algorithm established on the basis of Dijkstra algorithm [20]. Its core is cost function, as shown in formula (1).

$$f(n) = g(n) + h(n) \quad (1)$$

A-Star algorithm selects the node with the smallest cost function to expand each time. g(n) represents the path length from the starting node to the current node, which is a certain value. h(n) represents the estimated value from the current node to the target node, also known as the heuristic value, as shown in formula (2). Heuristic value h(n) is used to guide the search to expand to the target node, and the node with smaller heuristic value should be selected during the path search. The algorithm flow is shown in Fig. 5, and when the heuristic value is less than or equal to the real distance between the current node and the target node, A-Star algorithm can search the optimal path. The algorithm does not need to traverse all nodes, so the search speed and efficiency are high. The disadvantage is that when the local graph is large, the search path expansion may require a large number of nodes, and the algorithm cannot meet the real-time requirements.

$$h(n) = \sqrt{\left(x - x_{goal}\right)^2 + \left(y - y_{goal}\right)^2} \quad (2)$$

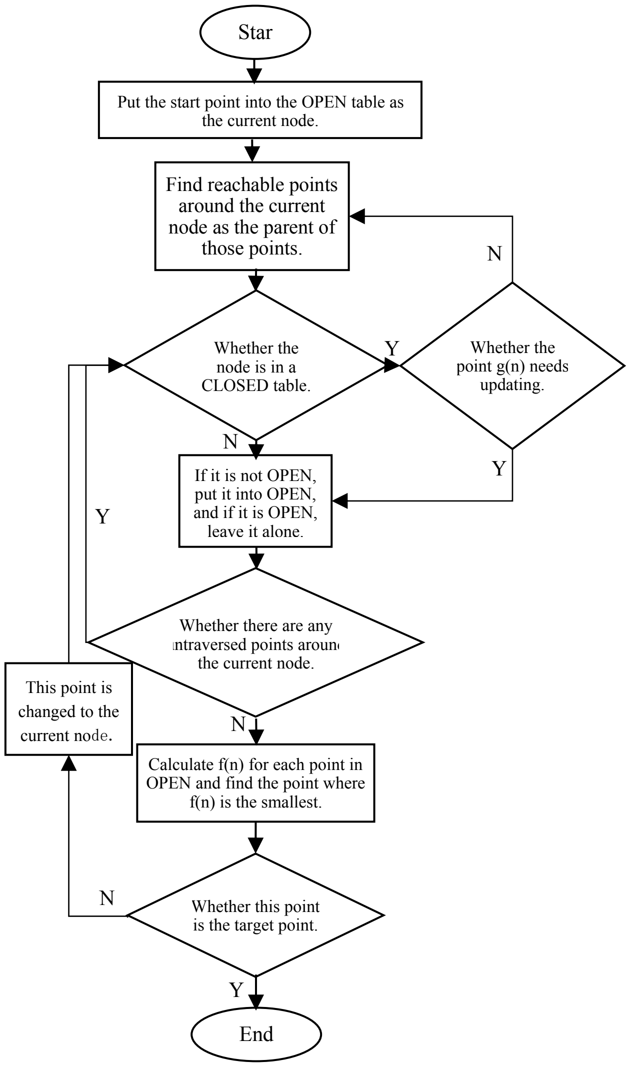

Fig. 5. A-Star algorithm flow chart

In addition to the shortcomings of real-time performance, A-Star algorithm also has the following problems. First, if the cost function of the introduced heuristic information cannot be completely correct, the deleted node may be one of the nodes of the optimal path. Second, it may cause the search process to form a loop and fall into a "dead cycle". Therefore, researchers have improved A-Star algorithm from different entry points and different use environments.

In literature [21], the region of the map is divided according to the density of the road network of the map. The heuristic number of A-Star algorithm is added with two factors, direction and distance, and the heuristic factor determining the weight of the direction information is increased, which improves the success rate of searching the optimal path and solves the "dead-loop" problem. In order to solve the problems of A-Star algorithm in larger scenarios, such as high memory overhead and long computing time, in literature [22], hop points are used to replace a large number of unnecessary nodes that may be added to Open List and Closed List in A-Star algorithm in the expansion process, thus improving the pathfinding efficiency. Literature [23] improves the security and smoothness of A-Star algorithm in view of its shortcomings in security and smoothness. Firstly, the security threat cost of the node is defined according to the minimum distance between the node and the obstacle, and it is introduced into the evaluation function of A-Star algorithm to improve the security of the planned path. Secondly, the planned path is smoothed and optimized, and the path evaluation mechanism is introduced in the smooth operation process to ensure that the generated value of the smooth path does not increase.

B. Path Planning Algorithm Based on Sampling

Sampling-based path planning algorithm does not need to model the environment of the state space, but uses random sampling points to approximate the potential environment space, and then searches the sampling points to get the feasible path. Common sampling-based path planning algorithms mainly include Rapidly-exploring Random Trees (RRT) [24] and Probabilistic Roadmap Method (PRM) [25].

1) Rapidly-exploring Random Trees Algorithm

The Rapidly-exploring Random Trees algorithm is a random sampling algorithm with incremental growth and a search method based on probability sampling. Through the random sampling points in the state space, the search is directed to the blank area, so as to find the planning path from the starting point to the target point. Node expansion of RRT algorithm is shown in Fig. 6. In the free-space C_{tree}, the starting point is denoted as q_{init}, and the new random point is denoted as q_{rand}. The current tree is traversed to find the point closest to q_{rand} point in the tree and denoted as q_{near}. Starting from q_{near} point, a fixed step is extended to q_{rand} point to obtain a new node and denoted as q_{new} to judge whether the q_{new} point meets the obstacle constraint, that is, whether there is a collision with the obstacle. When there is no collision with the obstacle, add the q_{new} point to the tree. If not, repeat the above steps until a collision free path from q_{init} point to q_{goal} point is found. This algorithm can solve the problem of high-dimensional and complex path planning, but the disadvantage is that if there are a large number of obstacles in a small space, the convergence speed will decrease, and this algorithm has certain randomness, so the path generated is not the optimal solution [26].

In view of the problem that the number of obstacles affects the convergence speed, literature [27] improved the growth mode of random tree to make it grow towards the target point, selected a measure function with low complexity to improve the solving speed, and embedded Dijkstra algorithm for optimization, so as to successfully avoid the threat of obstacles in the environmental map. In view of the instability of RRT algorithm results, literature [28] combined with environmental constraints, vehicle constraints and kinematic constraints on the basis of the existing algorithm, abandoned the greedy thought of the original algorithm and introduced heuristic sampling node insertion algorithm to improve the speed and quality of path planning.

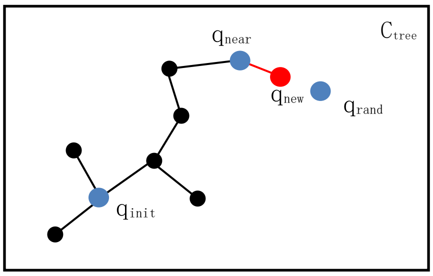

Fig. 6. RRT algorithm node expansion diagram

2) Probabilistic Roadmap Method Algorithm

PRM algorithm consists of two stages: learning stage and query stage [29]. In the learning stage, PRM algorithm collects samples in free space and connects the sampling points to form a probability diagram as shown in Fig. 7. In the query phase, any given starting point and target point are connected to the probabilistic path map established in the learning phase, and then the search based path planning algorithm is used to complete the path search from the starting point to the target point. If the connection cannot be made, the query fails. This algorithm is suitable for high dimensional path planning, but it is not complete when the sampling points are too few or the distribution is unreasonable. When there are narrow paths in the free space, due to uniform sampling, most of the sampling points finally obtained will exist in the wide space, and there will be relatively few sampling points in the narrow path, resulting in the loss of connectivity of the narrow path part of the probabilistic path diagram, which leads to the failure of path planning [30].

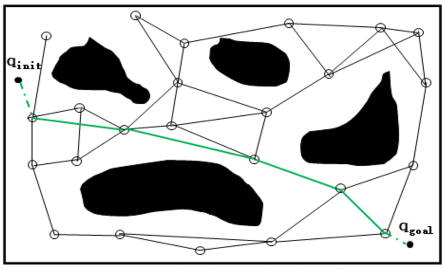

Fig. 7. PRM algorithm planning diagram

In reference [31], for the narrow channel problem of PRM algorithm, the artificial potential field is introduced into the planning environment, and the potential field force is applied to the points falling in the threat body to move them to the free space, so as to increase the number of nodes in the narrow channel and complete the construction of the road map without increasing the number of sampling times. According to the problem of too many obstacles and too few sampling nodes in the planning environment, literature [32] generates random nodes in the free space through random functions to replace nodes in the obstacles, increases the number of nodes in the free space when the number of sampling nodes remains unchanged, and coordinates with the improved node enhancement method to optimize the path.

C. Summary

The above algorithms are typical in the research of unmanned vehicle path planning. According to the performance, advantages and disadvantages of different algorithms, the applicable environment and conditions of each algorithm can be summarized, as shown in Table 1.

TABLE I. THE APPLICABLE ENVIRONMENT AND CONDITIONS OF THE ALGORITHM

Classif-ication	Algorithm Name	Applicable Environment And Conditions
Path planning algorithm based on search	Dijkstra algorithm	(1)Applicable to the more abstract graph theory level and directed graph, cannot deal with the existence of negative edge directed graph. (2)Solve the problem of traversal path planning. (3)Solve the problem of finding the shortest path and compare the length of the path without a specific path. (4)Apply to global path planning.
	A-STAR algorithm	(1)Suitable for more complex but not too large digraph. (2)Solve the problem of finding the shortest path. (3)Apply to global or local path planning. (4)This method is applicable when you need to obtain a specific path.
path planning algorithm based on sampling	RRT algorithm	(1)Applicable to two-dimensional plane and high-dimensional space. (2)Solve the path planning problem in complex environment and dynamic environment. (3)Apply to global or local path planning.
	PRM algorithm	(1)Suitable for high-dimensional space. (2)Solve the path planning problem in complex environment and dynamic environment. (3)Applicable to global or local path planning. (4)It is necessary to complete the whole process with the search-based algorithm.

It can be concluded from Table 1 that the sampling-based path planning algorithm represented by RRT algorithm and PRM algorithm is suitable for high-dimensional space, which is more convenient to solve the path planning problems in the complex and dynamic environment in practical research, and is feasible for both global path planning and local path planning. The search-based path planning algorithms represented by Dijkstra algorithm and A-Star algorithm are only applicable to two-dimensional planes and are mostly used to solve path planning problems in relatively single and static environments.

V. OTHER ALGORITHMS AND DEVELOPMENT DIRECTION

In addition to the typical unmanned vehicle path planning algorithm introduced above, Artificial Potential Field Method [33], Simulated Annealing Method [34], Neural Network Method [35] and other algorithms mainly used for local path planning are also common, which are mostly used to solve path planning problems in daily traffic. Intelligent Bionic algorithm such as Genetic algorithm [36] and Ant Colony algorithm [37], are prone to fall into local optimal problems and can be optimized by combining neural network algorithm, which has a high demand for samples. The current improved algorithm is mainly based on the combination of multiple algorithms and hierarchical optimization, which makes up for the shortcomings. However, there are problems of increasing algorithm complexity and slow convergence [38]. After further improvement, Genetic algorithm and Ant Colony algorithm can be used for route planning in the process of unmanned cargo transportation, namely VPR problem, and unmanned material transportation in battlefield environment.

In recent years, some reinforcement learning algorithms, such as Q-learning algorithm based on time-difference idea and Sarsa algorithm [39], have developed rapidly. However, trial-and-error Learning and state generalization of reinforcement Learning need to consume a lot of resources and their performance needs to be constantly improved. After performance optimization, it is more suitable for path planning in complex field battlefield environment with uneven road surface, many obstacles and strong uncertainty. The reinforcement learning algorithm mentioned above is data intelligence driven by model learning, which is also the mainstream technical route of the current development of artificial intelligence. Another way of the development of artificial intelligence technology is brain-like intelligence driven by cognitive bionics. Kind of smart brain is still in the laboratory research stage at present, many countries are actively developing class brain intelligence in order to solve data intelligent limitations and shortcomings, class brain intelligent learning, memory and recognition can be realized, conversation, reasoning, decision-making, such as intelligent cultivation, so kind of smart brain can solve unmanned vehicle path planning in complex environment of robustness is poor, poor adaptability problem. This can realize intelligent planning such as path planning and enemy tracking in the whole region, thus improving the automation and intelligence level of military equipment.

VI. CONCLUSION

Path planning algorithm plays an important role in the research of unmanned vehicles. With the rapid development and in-depth application of artificial intelligence and other advanced technologies, path planning algorithm is gradually improved and applied in unmanned combat platforms on land, water, air and underwater. The form of war is also accelerating to unmanned and intelligent evolution.

REFERENCES

[1] Z. B. Shen, B.B. Yong, Q.G. Zhou, L. Li, and G.J. Li, Principle and practice of unmanned driving.Beijing: China Machine Press,2020.

[2] X.J. Yu, Y.H. Huai, and Z.W. Yao, "Review and prospect of key technologies of construction vehicle unmanned driving," Journal of jilin university (engineering and technology edition), https://doi.org/10.13229/j.cnki.jdxbgxb20210038.

[3] Q.Y. Bao, S.M. Li, H. Shen, and X.H. Men, "Aurvey of local path planning for autonomous mobile robot," Transducer and Microsystems Technologies, vol. 28, issue 9, pp. 1-4+11, 2009.

[4] J. Xu, "The research of mobile robot path planning algorithm based on ant colony Algorithm," Beijing University of Chemical Technology, 2009.

[5] R.L. Ma, and Z.X. Guan, "Summarization for present situation and future development of path planning technology," The modern machinery, issue 3, pp. 22-24+7, 2008.

[6] F.C Huo, J. Chi, Z.J Huang, L.Ren, Q.J Sun, and J.L. Chen, "Review of path planning for mobile robots," Journal of Jilin University (Information Science Edition), vol. 36, issue 6, pp. 639-637, 2018.

[7] J.W. Gong, K. Liu, and J.Y. Qi, Model Predictive Control for Autonomous Vehicles (2nd Edition).Beijing: Beijing Institute of Technology Press, 2020.

[8] T. Wang, "The study if robotic path Planning and related simulation System based on ant colony algorithm," Xi'an University of Science and Technology, 2009.

[9] Z.H. Han, X.S. Fen, z. Lv, and L.Y. Yang, "An improved UAV oath Planning environment modeling method," Information and Control, vol. 47, issue 3, pp. 371-378, 2018.

[10] R.Xu, and J. Li, "A review of local path planning for autonomous vehicles," Automotive technology, issue 5, pp. 84-89, 2020.

[11] J.C. Yang, S.X. Li, and Z.Y. Cai, "Research and development of path planning algorithm," Control engineering of China, vol. 24, issue 7, pp.1473-1480, 2017.

[12] Y. Gu, D.Y. Zhang, and F.G. Ji, "Research on robot path search based on improved A* algorithm," Modern Information Technology, vol. 4, issue 13,pp.30-32, 2020.

[13] N.W. Wei, Y.Y. Jiang, Y.B. Liu, Y.F. Xin, and Y. Hong, "Method of PRM path optimization based on key nodes and smooth processing," Computer Engineering and Applications, vol. 56, issue 16, pp.118-123, 2020.

[14] J.M. Huang, Y.X. Wu,and X.Z. Lin, "Smooth JPS path planning and trajectory optimization method of mobile robot," Transactions of the Chinese Society for Agricultural Machinery, vol. 52, issue 2, pp.1-29+121, 2021.

[15] Y.D. Li, T.L. Ma, C.B. Chen, H.L. Wei, and Q.N. Yang, "Review of path planning algorithms for unmanned vehicles," Foreign electronic measurement technology, vol. 38, issue 6, pp.72-79, 2019.

[16] E.W. DIJKSTRA, "A note on two problems in conexion with graphs," Numerische Mathematik, vol.1, issur 1, pp. 269-271, 1959.

[17] P.E. HART, N.J. NILSSON, and B. RAPHAEL, "A formal basis for the heuristic determination of minim-um cost paths," AcmSigart Bulletin, vol. 4,issue 37, pp.28-29,1972.

[18] G.L. Zhang, X.M. Hu, J.F. Chai, L. Zhao, and T. Yu, "Summary of path planning algorithm and its application," The modern machinery, issue 5, pp.85-90, 2011.

[19] M.S. Guo, and T.F. Shi, "Research on robot path planning based on Improved Dijkstra algorithm," Electrical engineering technology, issue 20, pp.22-23+157, 2020.

[20] L.J. Ren, Y.S. Liu, and M.N. Chai, "Review of path planning method based on unmanned vehicle obstacle avoidance," Computer Science, vol. 45, issue 10A, pp.203-205, 2018.

[21] Y.H. Qi, Z.P. Yang, and Q.H. Huang, "Improved Path Planning algorithm based on A* Algorithm," Information and Electronic Engineering, vol. 7, issue 4, pp.326-329, 2009.

[22] X.Zhao, Z. Wang, C.K. Huang, and Y.W. Zhao, "Mobile Robot Path Planning Based on an Improved A* Algorithm," Robot, vol. 40, issue 6, pp.903-910, 2018.

[23] H.M. Li, M.L. Li, and L. Yang, "Safe Path Planning for Mobile Robot Based on Improved A~* Algorithm," Computer Simulation, vol. 35, issue 4, pp.319-324, 2018.

[24] J.J. Kuffner, S.M. Lavalle, "RRT-connect An efficient approach to single-query path planning," IEEE International Conference on Robotics and Automation, 2000.

[25] L.E. KAVRAKI, P. SVESTKA, and J.C. LATOMBE, "Probabilistic roadmaps for path planning in high-dimensional configuration spaces," IEEE Transactions on Robotics and Automation, vol. 12, issue 4, pp. 566-580, 1996.

[26] A.A. Doshi, A.J. Postula, and A. Fletcher, "Development of micro-UAV with integrated motion planning for open-cut mining surveillance," Microprocessors and Microsystems，vol. 39, issue 8, pp. 829-835, 2015.

[27] Z.Y. Liang, F.X. Chen, and W. Wei, "An improved RRT* path planning algorithm," Journal of Changchun University of Technology, vol.41, issue 6, pp.602-607, 2020.

[28] S.Y. Pan, and X.R. Xu, "Improved RRT*- based motion planning algorithm for mobile robot," Journal of Shanxi University (Nat. Sci. Ed.), vol. 40, issue 2, pp.224-254, 2017.

[29] M. Li, Y.Y. Zhou, and L. Huang, "Distance transform based PＲM path planning algorithm," Information Technology and Network Security, vol. 37, issue 3, pp.74-79, 2018.

[30] D. HSU, L.E. KAVRAKI， and J.C. LATOMBE, "On finding narrow passages with probabilistic road map planners," Robotics: The Algorithmic Perspective: 1998 Workshop on the Algorithmic Foundations of Robotics, pp.141-154, 1998.

[31] Y. Liu, W.G. Zhang, and G.W. Li, "Study on path planning based on improved PRM method," Application Research of Computer, vol. 29, issue 1, pp.104-106+139, 2012.

[32] S.X. Zou, P. Wang, and X. Han, "Improved Path Planning Algorithm Based on PRM," Modular Machine Tool & Automatic Machining Technigue, issue 1, pp.1-3, 2019.

[33] Z.Y. Chen, "Research on robot path planning based on artificial potential field Method," Yanshan university, 2016.

[34] X.M. Zhen, D.P. Gu, and X.S. Liu, "Robot path planning based on grid method with simulated annealing," Microcomputer Information, issue 5, pp.247-248+279, 2007.

[35] W.L. Xu, k. Tso, "Sensor-based fuzzy reactive na-vigation of a mobile robot through local targ-et switching," IEEE Translations on System，and Cybernetic，vol.29, issue 3, pp.451-459, 1999.

[36] J.J. Cui, "Research on Path Planning of Mobile Robot Based on Genetic Algorithm," Xi 'an University of Science and Technology, 2010.

[37] S.C. Zhang, J.X. Pu, Y.N. Si, and L.F. Sun, "A review of the application of ant colony algorithm in mobile robot path planning," Computer Engineering and Applications, vol. 56, issue 8, pp.10-19, 2020.

[38] C.Y. Wang, P. Liu, and H.Z. Qin, "A Review of Intelligent Path Planning Algorithms for Mobile Robots," Sensors and Microsystems, vol. 37, issue 8, pp.5-8, 2018.

[39] Y.N. Zhao, "Research of path planning problem based on reinforcement learning," Harbin Institute of Technology, 2017.