

Application Of Path Planning in Navigation Systems

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Abstract. Navigation systems have a wide range of applications in today's society, and path planning technology is one of the most important applications in navigation. With the rapid development of autonomous driving, robotics, and intelligent transportation systems, efficient and accurate path planning has become increasingly critical for enhancing operational safety and efficiency. The growing complexity of application environments further drives the demand for more adaptive and robust planning algorithms. This paper mainly describes the specific application of path planning technology in navigation. Firstly, it summarizes the main techniques and algorithms in path planning, which mainly include the techniques of environmental information acquisition and training on historical environmental information data, as well as algorithms such as BFS, Dijkstra and A* and some of the improvement methods. Then, path planning is analyzed specifically in practical applications, such as in AUVs, through a three-dimensional path planning model for innovative applications. This paper will mainly focus on the algorithms and practical applications of path planning to provide a comprehensive summary of path planning technology.

Keywords: Navigation system; Path planning; Environmental information acquisition; Model construction.

1. Introduction

Since the 1960s, the United States has launched the first navigation satellite, and in 1978, it developed a complete GPS navigation system. China also completed construction of the BeiDou navigation system in 2024. With the improvement of the global satellite navigation system, the navigation system has been more widely used in various fields, such as integrating all kinds of carriers, integrating with traffic information through navigation, positioning mobile devices can be accurately positioned through navigation, and using robots can be used for obstacle avoidance and control through navigation. The most important part of these applications is the path planning technology in the navigation system.

Path planning technology aims to automate the calculation of paths by analyzing data, which is one of the important functions of intelligent systems and navigation systems [1]. Three main algorithms for path planning techniques have been developed since then, which are BFS, A*, and Dijkstra. There are also many excellent examples of path planning in practical applications, such as the TRIFO Group's integration of AI technology in cleaning robots, which optimizes a high-precision modelling scheme to automatically identify the room environment in order to complete cleaning. However, the traditional path planning algorithms are limited by static maps, and they lack the ability to plan in real time for dynamic objects, making it difficult to react in a timely manner when encountering unexpected situations, such as cleaning robots often colliding with obstacles in complex environments. There is also a high dependence on accuracy. Therefore, the current path planning technology cannot adapt to the complex and changing environment and different needs.

The purpose of this paper is to summarize the specific applications of path planning techniques in navigation systems, mainly discussing the main techniques used, and analyzing and comparing the three main algorithms of BFS, A* and Dijkstra in path planning, as well as the main applications of path planning techniques in the fields of AUV and robots.

2. The Related Techniques and Algorithms in Path Planning

2.1. The Concept of Path Planning

In order to understand the path planning techniques, it is first necessary to clarify its basic definition concept. Path planning technique is a method of generating a path by connecting a series of coordinate points or curves on a map between a start location and an end location. The start location and end location are also known as the Start Point and Goal Point [2].

2.2. The Main Techniques in Path Planning

The two main techniques used in path planning are the collection of environmental information and the training of historical environmental information data. A path planner should have a good understanding of the environment [3]. So, the acquisition of environmental information is very crucial. The acquisition technique of environmental information is the sensor by sensing the environmental parameters such as physical, chemical and biological quantities and converting them into electrical or digital signals. Therefore, in this process, it needs to pay attention to the collection and processing of environmental information and the transmission of information. The collection of information is mainly for the environment of temperature changes, humidity levels, light intensity and other real-time collection [1]. However, in the initial raw data, there will be a lot of interference factors, such as noise and other interference, so the data need to be further processed through data cleaning, data processing, feature extraction, pattern recognition and other methods. In addition, it is for the timely transmission of information, timely transmission can ensure the accuracy of data. The collected information will be transmitted to the cloud data centre for data storage and analysis, which includes wired and wireless communication, such as WIFI, Bluetooth, Ethernet, etc [1].

Secondly, it is the training for the historical environmental data. The training of historical environmental information data refers to the use of environmental data collected in the past and trained by machine learning and data analysis techniques, so as to extract the regularity, trend and characteristics of the environment, and to provide support for environmental prediction, intelligent decision-making, etc [1].

The main sentence types in historical environmental data information mainly include map data, obstacle information, target point data, environmental change data, environmental feedback data, environmental model data, learning history data, path planning data and optimization strategy data. Among them, map data and obstacle data are mainly used to identify the structure and characteristics of the environment and the location and type of obstacles in the environment through sensors, cameras or online maps, and then the data are processed through data fusion, map construction, feature extraction and other methods. Target point data requires human input and demand from the user to obtain the target point to be reached, and then the target point coordinates are recorded and the target point markers are processed. Environment change data, environment feedback data, and environment model data are mainly used to identify the dynamic change information in the environment through real-time sensor data and detection of the environment and the feedback information of the environment after the robot's action, and then process the data through dynamic data processing and feedback analysis. Learning history data, path planning data and optimization strategy data are collected through training datasets, model parameters, simulations, etc., which describe the robot's learning from past experiences, the results of path planning in different scenarios and the optimization of path planning decisions.

Historical environmental information data also suffers from missing values, outliers, etc., so data cleansing is also needed to remove invalid and abnormal data, as well as normalization and standardization to unify the data to scale and avoid errors [1]. The machine learning model is then allowed to train through feature engineering, evaluated and optimized to further improve the effectiveness of the model.

2.3. The Main Algorithms in Path Planning

The application of algorithms is the core of the path planning technique, through which the algorithm can go to the optimal path in the environment. The steps of the algorithm are first to obtain the relevant map information, such as terrain, obstacles, target points, etc., and then carry out modelling. After the modelling is completed, the starting point and the end point are determined, and finally the appropriate algorithm is selected. The main algorithms commonly used at present are breadth-first search (BFS), depth-first search (DFS), Dijkstra's algorithm, A* algorithm, etc [1].

For the BFS and Dijkstra algorithms, it is possible to reproduce the BFS or Dijkstra algorithms in the same way on the grid by means of a new multi-layer network consisting of only transformed pooling layers (T-POOL), which is mainly related to the method of generating gradient maps and performing path searches by using distance transformations [4]. Each T-POOL network consists of L identical layers the network uses different types of transformations, weighted and biased by B-filters of size 3×3 . Where in BFS algorithm the cost of all moves is uniformly 1 and Dijkstra's algorithm these values correspond to the cost of moving horizontally or vertically as well as diagonally i.e. 1 and $\sqrt{2}$ and Dijkstra's algorithm performs a decimation algorithm [4]. On the other hand the BFS algorithm is mainly applicable to unweighted graphs, i.e. it focuses more on whether there are links between nodes and ignores factors such as the actual distances, so sometimes it is not guaranteed that the shortest path is found. The Dijkstra algorithm is mainly applicable to weighted graphs, i.e. each side of the graph has a weight value associated with it, which represents information such as distances to that side, and this method finds the optimal path more accurately. The A* algorithm is currently the most dominant algorithm, and as opposed to BFS and Dijkstra's algorithm, the A* algorithm incorporates an evaluative heuristic function, i.e., an estimate or evaluation of the cost of future moves, which allows for a more aligned search. The A* algorithm is technically a modified version of the original Dijkstra's algorithm, which is considered to be the best-preferred search algorithm, which means that the cost of moves per iteration is the lowest. A* selects the closest, most efficient, and immediately visible path, resolving all possible "shortest paths" [5]. Because the A* algorithm requires more attention to the development of heuristic functions, it is relatively memory inefficient.

2.4. The Optimization of Related Algorithms

For the A* algorithm, although it is a very efficient algorithm, in complex environments, its planned paths sometimes do not fully meet the actual motion characteristics of mobile robots [4]. Therefore, the search efficiency and the quality of paths of the A* algorithm can be optimized and improved, which can be improved in terms of the search method, evaluation function and search strategy of A* algorithm [6].

2.4.1 The Search Method

The traditional A* algorithm usually adopts the 8-neighbourhood search method, i.e., searching 8 neighbouring nodes around the current node, but the limitation of the target point orientation may search unnecessary raster nodes, resulting in the waste of computing time [6]. So, it is improved to search around the nearest passable nodes in front and behind the obstacle in the whole search process, i.e. a kind of search method combining triangular boundary and three-neighbourhood search - triangular boundary search [6]. In this method, the traditional 8-neighbourhood search method is replaced by searching for passable nodes on the right triangle boundary by generating right triangles and searching for paths along their boundaries, and the 8-neighbourhood search of the traditional A* algorithm is optimized by expanding the nodes that have the lowest cost on the boundaries of the right triangle edges. The approach is shown in Fig. 1 [6].

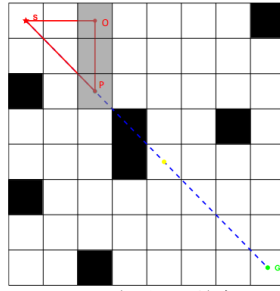


Fig. 1 Schematic diagram of triangular boundary search [6]

2.4.2 The Evaluation Function

The improved A* algorithm adds passable sub-nodes to the open list by triangular boundary or three-neighbourhood search, and selects the node with the lowest cost for expansion based on the evaluation function. Choosing an appropriate evaluation function can directly affect the efficiency of mobile robot path planning. Therefore, based on two different search methods, segmented evaluation functions are used to adapt to the search characteristics of different regions.

The rating function of the traditional A* algorithm is: where n is the current node, $f(n)$ is the actual cost from the starting point to the current node, and $g(n)$ is the estimated cost from the current node to the goal point [6].

However, when the mobile robot uses triangular boundary search, the geometric constraints of the triangular boundary are added to the heuristic function, and the penalty term based on the triangular boundary is introduced to accelerate the search along the straight-line direction, and when the mobile robot uses three-neighbourhood search, the path search is accelerated by dynamically adjusting the heuristic weights and introducing the surrogate value of the parent node [6].

2.4.3 The Search Strategy

In traditional mobile robot path planning, the A* algorithm starts from the starting point and gradually searches towards the target point, and the search will traverse the whole map, resulting in a larger search space and longer computation time [6]. In order to reduce the space searched by the robot, a bidirectional alternating search strategy is introduced. The basic idea of this strategy is to start searching from the starting point and the target point at the same time, and to alternate the search until the two search fronts meet [6].

3. The Specific Applications and Examples of Path Planning

3.1. The Applications in Long-Range Autonomous Underwater Vehicles (AUV)

In AUV, the main innovative application is the 3D path planning model, because the path planning of AUV needs to meet many conditions. Firstly, when navigating, it needs to maintain a certain distance from the seafloor, but at the same time, it also needs to ensure that the distance is within the effective range of sonar detection [5]. Secondly, the path of the AUV also needs to satisfy all the constraints, such as differential constraints, AUV dive depth constraints, and obstacle constraints [5]. Finally, the AUV should also be in a region where it is easy to match the terrain as much as possible [7].

The 3D path planning applied in AUV includes vertical plane constraints and horizontal plane constraints, the relationship of which is shown in Fig. 2 [7].

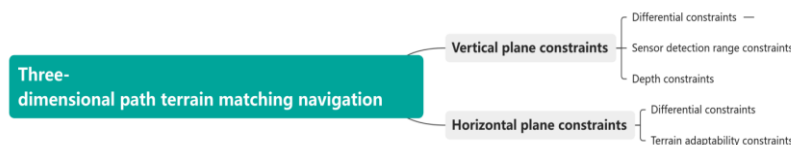


Fig. 2 3D path planning execution diagram [7]

Meanwhile, the most important thing in path planning is to define the fitness function for solving the path, which can evaluate the advantages and disadvantages of different paths in order to plan the best path.

3.2. The Application in Cleaning Robots

Path planning techniques also have an important role in cleaning robots. In indoor home environments, cleaning robots are prone to encountering sudden dynamic obstacles during the cleaning process, so it is important to complete the cleaning task while being able to safely avoid obstacles through reasonable path planning [8].

Path planning system in the cleaning robot is mainly used in the absence of environmental maps, can be segmented to give the best exploration of the target point and moving path, according to this path walking can be updated to the maximum extent possible to improve the environmental map, so as soon as possible to complete all the environment to explore the generation of a complete environmental map, and the map to carry out the necessary management, to facilitate the subsequent planning and navigation [2]. Then, after having the necessary information, it is able to output the path to arrive at the target point, which has a short length, safe and collision-free in movement, and has the shortest possible execution time [2]. Finally, it is able to give a full-coverage path for cleaning the specified idle area, which satisfies safety without collision, short path length and short cleaning time [2]. Better path planning techniques allow the cleaning robot to better avoid obstacles and provide important decisions to complete the work more efficiently and safely.

One of the important features in cleaning robots is reinforcement learning, which has shown remarkable ability in negotiating with complex environments. Its ability to negotiate in complex environments and its agility in performing difficult tasks are remarkable [9]. Reinforcement learning stands for learning from feedback and errors, for example, babies can learn how to walk or talk by reinforcement from their parents.

For a robot, reinforcement learning involves selecting a suitable algorithm through which the next action is performed, after that the environment receives the effect of the action is collected and then the system enters a new state or rewards the robot and finally gives feedback to the robot for the next action.

3.3. The Application in the Indoor Navigation System

An indoor navigation system is a device that monitors the user's location, designs a reasonable route and guides the user along the path to the desired destination [10]. In many large indoor scenarios, indoor navigation technology is required. For example, in large airports, it is not easy to find the correct check-in counters or boarding gates, or it is not easy to find parking spaces in some underground car parks. Indoor navigation systems can help us navigate to the correct location quickly.

When indoors, outdoor navigation systems will no longer work, so indoor navigation systems must be used to facilitate individuals unfamiliar with facility maps to navigate indoors and thus avoid obstacles [10]. At the same time, indoor navigation systems often lack flexibility for adapting to different environments, as this often requires individual customization for a specific building. As new applications must be developed from the start for each new building, this customization requirement leads to significant development efforts and high costs [10]. Current indoor navigation systems make indoor navigation more challenging than outdoor environments due to degraded signal quality due to thicker walls, lack of GPS signals, and the inability to maintain a line of sight with orbiting satellites [10].

Certainly, researchers have found that these problems can be solved through the use of Augmented Smart Indoor Navigation Systems using Augmented Reality (ESINS_AR). The use of ESINS_AR technology can provide a cost-effective and intuitive solution for indoor navigation by superimposing digital navigation signals from the system onto the physical environment, which allows visual markers located within a building to provide users with real-time smartphone navigational aids to ensure that they are guided to their destinations more efficiently [10].

A* algorithm is also a very important part of indoor navigation systems, which minimizes the total cost of the path while efficiently determining the shortest path from the start node to the destination node. In the A* algorithm, heuristic functions can be customized to solve a specific problem to meet the requirements of the application, and at the same time, it can focus on reasonable paths while avoiding unlikely paths during the search process [10]. So, A* is widely used in many practical path-finding and optimization problems as it ensures the shortest path with appropriate heuristics.

4. Conclusion

This paper is mainly a summary of the application of path planning techniques in navigation systems, outlining the important applications of path planning techniques in navigation systems. Firstly, it summarizes and compares the concepts, technical requirements and algorithms of path planning, as well as some improvement methods; secondly, it summarizes the specific applications of path planning technology in AUV and cleaning robots. At present, the path planning technology has been relatively mature, and the algorithm may be continuously optimized and improved in the future, for example, its decision-making can be trained more to adapt to more complex decision-making problems; or the path planning can be integrated with other related aspects such as vision and language, to continuously promote the development of the path planning technology.

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