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Research on Intelligent Ship Path Planning Method

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Abstract

With the rapid development of science and technology, the shipbuilding industry has ushered in an information revolution, and the level of ship intelligence is increasing day by day. Intelligent ships bring new opportunities and challenges to the development of the shipbuilding industry. Intelligent navigation is one of the core technologies that constitute intelligent ships. It achieves autonomous navigation, path optimization, and real-time decision-making for ships by integrating advanced sensors, data processing, and artificial intelligence algorithms, thereby improving navigation efficiency and safety. This article will focus on the route planning methods for intelligent navigation of intelligent ships, exploring aspects such as environmental modeling, navigation constraints, and algorithm design, thus providing reference significance for the development of autonomous navigation technology for intelligent ships.

Keywords

Intelligent Ships; Intelligent Navigation; Environmental Modeling; Navigation Constraints; Algorithm Design.

1. Introduction

Intelligent navigation, especially autonomous route planning for intelligent ships, has become a research focus in the field of ocean engineering[1]. With the development of artificial intelligence, the Internet of Things, and automation technology, intelligent ships can autonomously plan routes based on environmental changes without the need for manual control[2]. This technology not only improves the safety of navigation, but also optimizes voyage efficiency, reduces energy consumption, and promotes the development of green shipping. However, achieving efficient route planning in complex marine environments remains a major challenge in intelligent navigation.

This paper reviews the core technologies of autonomous route planning for intelligent ships, including environmental modeling, navigation constraint design, and algorithm optimization. It first introduces environmental modeling methods, including common methods such as grid methods, topological graph methods, and visibility graph methods; next, it explores how to ensure navigation safety during the planning process by considering constraints such as ship kinematic parameters, collision avoidance rules, and ship domains; finally, it analyzes the application of graph search algorithms, sampling-based algorithms, and intelligent optimization algorithms in path planning, evaluating their efficiency and applicability. This article provides a theoretical framework and technical guidance for the research and practice of route planning for intelligent ships through a comprehensive analysis of these technologies.

2. Intelligent Navigation Environment Modeling Method

Intelligent navigation environment modeling methods are crucial for autonomous ship navigation, addressing environmental factors for safe and efficient path planning[3]. These methods include geometric modeling, graph-based modeling, physics-based modeling,

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constraint-based modeling, and uncertainty-based modeling. Each method plays a unique role in facilitating intelligent navigation in dynamic and complex marine environments.

In the field of intelligent ship route planning research, the most common modeling methods are the grid method, visibility graph method, and topological graph method. This article will focus on discussing these three modeling methods.

2.1. Grid-based Method

The grid-based method is one of the most widely used environmental modeling techniques in path planning algorithms[4]. It discretizes a specified area into grid cells, where each cell represents a state, such as passable or impassable areas (obstacles). This method's simplicity and effectiveness allow for clear representation of complex obstacle distributions, with path planning conducted through graph search algorithms like A*. It is suitable for both static and dynamic environments, supporting path updates and making it widely applicable in complex settings. However, the method's accuracy depends on the grid size; large grid cells may lead to imprecise path planning, while smaller cells can increase computational load, affecting efficiency, especially in large-scale, high-resolution environments. Furthermore, the grid-based method may experience lag in fast-changing dynamic scenarios, as map updates and path replanning may not be fast enough. Despite these limitations, it remains a key environmental modeling method for high-precision and dynamic obstacle avoidance, particularly in obstacle-dense environments. Figure 1 shows the grid-based method illustration.

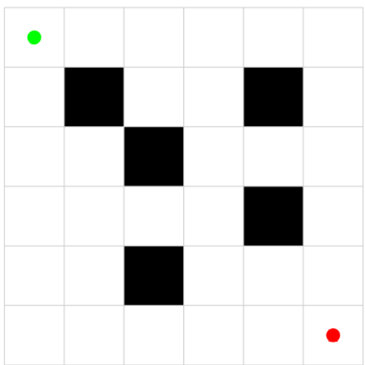

Fig 1. Grid-based map

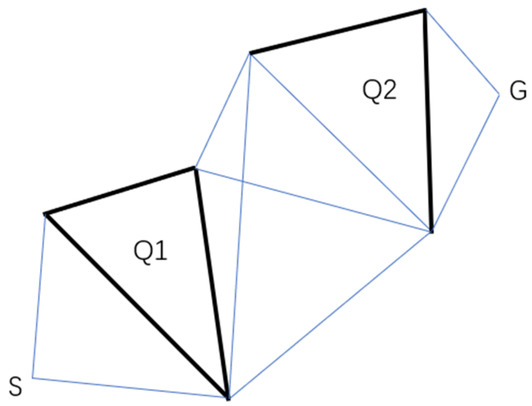

Fig 2. Visibility graph map

2.2. Visibility Graph Method.

The visibility graph method uses geometric polygons to represent obstacles in the environment, as shown in Figure 2. In this method, Q1 and Q2 symbolize two different obstacles. First, the starting points, target points, and vertices of these polygons are defined. Then, lines connecting these points are drawn (S and G in Figure 2 represent the starting and target points). These connections must not intersect with any obstacles; lines that do not intersect with obstacles are considered "visible," while lines that intersect with obstacles are marked as "invisible." The complete graph formed by all visible connections is called the visibility graph. Using this method for environmental modeling transforms the optimal path planning problem into determining the shortest path problem.

2.3. Topological Graph Method.

The topological graph method was originally proposed by Kuipers based on graph theory and has now become an important tool for ship route planning[5]. It describes and analyzes the relationships between nodes and connections in the maritime network without focusing on specific geographical distances. In this method, key navigation points (such as ports and

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channel intersections) are treated as nodes, and waterways are viewed as edges connecting these nodes, thus forming a complete network. Researchers can use the topological graph to optimize paths, identifying the shortest, most economical, or safest routes to improve efficiency and safety. The advantage of this simplified method lies in its abstraction of complex navigation systems, allowing researchers to focus on network structure and function rather than geographical details. Therefore, it is very suitable for large-scale planning, such as global shipping network optimization and port logistics design, and can be effectively combined with algorithms like Dijkstra or A* for path searching. However, this method has limitations in applications that require precise geographical information, as it ignores physical distances and terrain details. Additionally, establishing the initial model requires accurate data to ensure its effectiveness.

3. Navigation Constraints

In the context of intelligent ship path planning, the design of navigation constraints is essential to ensure both the safety and efficiency of autonomous navigation. This chapter reviews key constraints, including ship kinematic limitations, maneuvering characteristics, collision avoidance rules, and the ship domain. These constraints form the foundation for developing practical and robust path planning algorithms, enabling ships to navigate safely within dynamic and complex maritime environments.

3.1. Ship Kinematic Limitations

The constraints of ship kinematics play an important role in the ship path planning process, directly affecting the feasibility and safety of the ship's route[6]. Due to the limitations of the ship's turning performance based on its size and maneuvering characteristics, path planning needs to consider the ship's minimum turning radius to avoid unrealistic or highly dangerous turning designs. At the same time, the ship's speed limitations, maneuvering response time, and external dynamic effects, such as water flow and wind, must also be taken into account in the path planning. These constraints ensure the feasibility and safety of the ship during actual navigation.

3.2. Collision Avoidance Rules

The rules for vessel navigation and collision avoidance vary in different countries and regions, with the most widely applicable and authoritative being the International Regulations for Preventing Collisions at Sea (COLREGs). These rules play a crucial role in constraining the path planning of intelligent vessels. The rules clearly define the responsibilities and priorities for collision avoidance in various navigation scenarios, ensuring that vessels can safely maneuver and prevent collisions. For example, the rules require vessels to take avoidance measures based on their relative positions when encountering, crossing, or meeting each other, and specify the avoidance responsibilities of certain vessels in narrow channels. For intelligent vessel path planning, COLREGs provide clear behavioral norms, requiring path planning systems to adhere to these rules during real-time navigation, thereby ensuring navigational safety and optimizing path efficiency. Therefore, COLREGs provide an important constraint framework for the autonomous decision-making and path optimization of intelligent vessels.

3.3. Ship Domain

The ship domain is an important concept in ship collision risk assessment, referring to a defined safety area surrounding a ship, within which navigation does not pose a collision risk. When other vessels enter this area, it indicates a potential danger of collision. The ship domain is typically defined based on factors such as the size and maneuvering characteristics of the ship, used to assess the collision risk between the ship and other vessels or obstacles. The definition of this domain not only supports collision avoidance decisions but also needs to be combined with the kinematic constraints of the ship to ensure the safety and feasibility of path planning[7].

4. Research Status of Path Planning Algorithms

Ship path planning algorithms can usually be classified based on their search strategies, optimization objectives, and computational methods. Common classification methods include graph search-based algorithms, sampling-based algorithms, and optimization-based algorithms[8]. Each classification has typical algorithm models that are suitable for different path planning scenarios based on the characteristics of the algorithms. The specific classifications and algorithm characteristics are shown in Table 1. This chapter will discuss the A* algorithm, RRT algorithm, and dynamic window approach as representatives among three path planning algorithms.

Table 1. Classification and Comparison of Ship Path Planning Algorithms

Category	Algorithm	Applicable Scenarios	Advantages	Disadvantages
Graph-based Algorithms	A* Algorithm	Deterministic environments, known obstacles, navigation constraints	Efficient in finding the shortest path, heuristic functions can improve search efficiency	Poor adaptability to dynamic obstacles or uncertain environments, paths may not
	Dijkstra Algorithm	Finding the shortest path from all nodes to the target node in a network	Guarantees the shortest path, suitable for weighted graphs	Less efficient, especially in large graphs, poor adaptability to dynamic changes
Sampling-based Algorithms	RRT (Rapidly-exploring Random Tree)	High-dimensional spaces, complex obstacle environments	High computational efficiency, suitable for complex environments	Path quality is low, generated paths may not be optimal or smooth
	PRM (Probabilistic Roadmap Method)	High-dimensional, complex environments, efficient when the environment model is known	Avoids unreachable areas, flexible and easy to extend	Slow response to dynamic environments, path quality not always optimal, preprocessing time is long
Optimization-based Algorithms	DWA(Dynamic Window Approach)	Real-time control and path planning in dynamic environments	Strong real-time performance, suitable for dynamic environments, considers kinematic and dynamic constraints	High computational complexity, requires strong tuning capability
	PSO (Particle Swarm Optimization)	High-dimensional, multi-objective optimization problems, especially complex objective functions	Global search capability, avoids local optima, adaptable to different problems	Sensitive to initial conditions, long computation time, accuracy may not always be high

4.1. A* Algorithm

The A* algorithm is a widely used heuristic algorithm in path planning and graph search. It finds the optimal path from the starting point to the endpoint by combining greedy strategies and the concept of shortest path search. Specifically, the A* algorithm evaluates the priority of each node based on the actual cost (the cost from the starting point to the current node) and the estimated cost (the estimated cost from the current node to the endpoint). By continuously expanding the node with the lowest cost, it ultimately finds the shortest path. In recent years, its research focus has mainly concentrated on optimizing heuristic functions, dynamically adjusting search strategies, and improving the algorithm's adaptability to complex environments.

4.2. Rapidly-exploring Random Tree (RRT)

Rapidly-exploring Random Tree (RRT) is a path planning algorithm based on random sampling, widely used for path search in high-dimensional spaces. The basic idea of RRT is to start from the initial point, randomly generate a series of nodes, and expand them into the search space, gradually constructing a tree structure[9]. Each time it expands, the algorithm selects a random target point and extends new nodes in the direction from an existing node in the tree to the target point, until a path from the start point to the endpoint is found or a specified target area is reached. The advantage of RRT is its ability to quickly explore complex, high-dimensional spaces and adapt to dynamic and uncertain environments.

Current research on RRT improvements mainly focuses on path optimization and sampling efficiency. For example, the RRT* algorithm achieves smoother trajectories by gradually optimizing path quality; in addition, improved sampling strategies and motion planning methods enhance the algorithm's adaptability and real-time performance in dynamic environments.

4.3. Dynamic Window Approach (DWA)

The Dynamic Window Approach (DWA) is a real-time control algorithm used for path planning of mobile robots and ships. It searches for optimal control inputs (such as speed and steering angle) within a local range by considering kinematic constraints, generating a smooth and feasible path. DWA defines a "dynamic window," within which the speed and acceleration comply with the robot's dynamic limitations, and then selects the optimal action to guide the robot to avoid obstacles and move forward[10]. In recent years, research on improvements to the Dynamic Window Approach (DWA) has mainly focused on kinematic modeling, computational efficiency, and adaptability to dynamic environments. Improvements include the introduction of artificial potential field methods to optimize obstacle avoidance, as well as the integration of machine learning to enhance the accuracy of control selection. At the same time, the research also aims to enhance the real-time adaptability of DWA to dynamic obstacles to improve its stability and robustness.

5. Conclusion

Path planning is a fundamental technology for intelligent ships to achieve smart navigation. This article discusses the current state of research on path planning for intelligent ships and commonly used methods, including environmental modeling, navigation constraints, and algorithm selection. With the rapid development of intelligent technologies across multiple fields, the scenarios for ship route planning will become more diverse, and the combination and innovation of algorithms will bring more possibilities to route planning, enhancing navigation safety while reflecting its economic and environmental sustainability. At the same time, governments and maritime organizations around the world are strengthening research and regulatory constraints on the direction of intelligent ship navigation. It is foreseeable that intelligent navigation and path planning will continue to be hot research areas in the shipbuilding industry, and researchers will constantly face new challenges, with intelligent navigation planning playing an important role in the new era of navigation.

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