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Performance Analysis of Dijkstra and A-star Algorithm in Maritime Navigation Pathfinding

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ABSTRACT

This study explores various algorithms and methodologies for path planning and decision-making in diverse environments, including maritime distribution and logistics. The research highlights the importance of COLREG rules in designing collision avoidance algorithms for Maritime Autonomous Surface Ships (MASS), emphasizing the need for algorithms that adapt to specific maritime parameters. A Multiple-Criteria Decision-Making (MCDM) approach combined with Dijkstra's algorithm is presented to optimize route distribution in logistics, taking into account parameters such as cost, distance, congestion, and risk. Experimental path planning methods using A-star and Dijkstra algorithms are discussed for navigating slag disposal sites that emit natural radiation, demonstrating the adaptability of these algorithms in hazardous environments. The study also investigates dynamic path planning algorithms, such as DAA-Star, which incorporate time and risk cost factors to enhance the safety and efficiency of navigation. Integrating various algorithms and considering specific environmental parameters can significantly improve path planning and decision-making processes in maritime and logistics contexts.

1. Introduction

The maritime industry is the heart of global trade and transportation, facilitating the movement of goods and people across oceans. In maritime navigation, avoiding bad weather conditions and marine traffic can enhance sailing efficiency and speed [1]. The effectiveness of maritime navigation serves as an alternative to reduce high operational costs caused by overly long and inefficient sea routes [2]. Besides saving time and costs, finding an effective route can have a vital impact on safety, as it helps avoid multi-ship encounters where two or more vessels risk collision [3]. Thus, implementing effective route planning influences crucial aspects of maritime operations.

Finding an effective route in the maritime field involves measuring the distance from the departure point to the destination. However, distance alone is not enough to determine an effective route that avoids multi-ship encounters. Additional variables, such as sea conditions, marine traffic, and weather, are required. These variables are represented as weights and implemented using a Graph data structure with Dijkstra's algorithm and the A* algorithm.

A comparison of the two algorithms is conducted to assess their performance, focusing on aspects such as computational time and time complexity. These elements are key in determining which algorithm is more efficient in finding the fastest route in maritime operations.

The A* algorithm, one of the algorithms for finding the shortest path, uses a heuristic approach [4]. Heuristics improve search efficiency by combining the actual distance to be traveled with an estimated distance to the destination. A* prioritizes routes that are likely to yield optimal solutions, significantly reducing the search space and resulting in faster computation and more efficient navigation. This heuristic approach makes A* widely used in complex maritime environments, especially where time and resource limitations are critical [5].

Studies have shown that A* can optimize routes between ports by reducing costs and emissions while prioritizing the safety and security of ship personnel. These studies demonstrate that A* improves route efficiency in terms of both length and travel time. A shorter, more efficient route directly impacts fuel consumption, lowering operational costs. Additionally, with reduced fuel consumption, emissions can be minimized, aligning with global efforts to reduce the environmental impact of maritime activities [6]. Furthermore, factors such as weather conditions, strong sea currents, and hazardous areas around ports can be taken into account with A*, ensuring the safety of personnel during the journey.

Another study explored the use of Dijkstra’s algorithm for calculating the shortest route. This research found that Dijkstra’s algorithm is effective in identifying the nearest route [7]. The algorithm works by evaluating all possible paths from the starting point to the destination, selecting the path that minimizes distance or time. Dijkstra's algorithm also allows users to choose routes, making navigation along the nearest path easier.

A comparative performance analysis of Dijkstra and A* in maritime navigation provides insights into their efficiency, accuracy, and computational requirements. Such an analysis helps identify the most suitable algorithm for specific maritime scenarios, contributing to the optimization of navigation routes [8], [9]. Understanding the strengths and limitations of these algorithms can inform the development of advanced navigation systems, enhancing both safety and efficiency in maritime operations. This study aims to contribute to the body of knowledge on maritime navigation and pathfinding algorithms [8], [10].

So far, no comprehensive review has been conducted comparing the performance of Dijkstra and A* in maritime route planning [11]. Existing research has focused on specific contexts, such as planning optimal paths in radioactive environments by comparing the performance of Dijkstra and A* in minimizing radiation exposure while navigating slag piles [2]. Other studies have explored improvements to Dijkstra's algorithm for ship routing, focusing on efficiency, optimization, storage, and real-world maritime applications [3]. Some research has discussed advances in navigation and collision avoidance, such as using the A* (DAA*) algorithm for planning routes for ships with multiple moving obstacles. However, there has been no specific review comparing the performance of these two algorithms in maritime navigation.

Based on this background, the objective of this article is to provide a comparative review of the performance of the Dijkstra and A* algorithms in maritime route planning. The research questions (RQs) for this study are as follows.

- RQ1: Why is path planning necessary?
- RQ2: What strategies are used to enhance the efficiency of path planning?
- RQ3: What are the limitations of the strategies used in maritime navigation?
- RQ4: How efficient are the algorithms in finding the fastest maritime routes?
- RQ5: What differences arise when using and not using these algorithms?

2. Methods

This article is a review, and the methodology used is explained below.

2.1. Article Search

The article search was conducted using databases from Google Scholar and ScienceDirect. The keywords used in the search were ("A-star Algorithm" OR "Dijkstra Algorithm" AND "Ship route planning"). Selected articles must have been published between 2019 and 2024. The materials reviewed include both articles and journals. The selection strategy was divided into four categories to address the five research questions.

Table 1: Categories of Papers Used

No	Journal or Article Category	Quantity
1	A* Algorithm	8
2	Dijkstra Algoritm	7
3	Comparison A* and Dijkstra Algorithm	1
4	Ship path planning and maritime	4

2.2. Article Review Process

After conducting a comprehensive literature search, the next step is to perform an in-depth review of the collected articles based on the formulated research questions. This review process involves several critical aspects, including the primary objectives of the research, the methods used, and the data collection techniques employed by the authors. Additionally, an evaluation of whether the findings and conclusions align with the empirical data gathered is a crucial component of this process.

The limitations identified in the studies, along with the strengths and weaknesses of each article, are essential elements for assessing the relevance of the article to the research questions. This process aims to ensure that each reviewed article provides significant contributions to answering the research questions and establishes a solid foundation for future studies.

3. Results and Discussion

3.1. Article Metadata

Table 2 are the metadata of 20 journal articles analyzed to answer the research questions.

Table 2: 20 articles metadata.

No	Author(s)	Year	Title	Journal Source
1	Miyombo Ernest Miyombo, Yong-kuo Liu , Chishinga Milton Mulenga, Anthony Siamulonga, Martin Chihango Kabanda, Phillimon Shaba, Chunli Xi, Abiodun Ayodeji	2024	Optimal path planning in a real-world radioactive environment: A comparative study of A-star and Dijkstra algorithms	Nuclear Engineering and Design
2	Helong Wang, Wengang Mao, Leif Eriksson	2019	A Three-Dimensional Dijkstra's algorithm for multi-objective ship voyage optimization	Ocean [1]Engineering
3	Zhibo He, Chenguang Liu, Xiumin Chu, Rudy R. Negenborn, Qing Wu	2022	Dynamic anti-collision A-star algorithm for multi-ship encounter situations	Applied Ocean Research
4	Shaher Alshammrei1, Sahbi Boubaker, and Lioua Kolsi	2022	Improved Dijkstra Algorithm for Mobile Robot Path Planning and Obstacle Avoidance	Computers, Materials Continua

5	Shan Liu, Hai Jianga, Shuiping Chen, Jing Ye, Renqing He, Zhizhao Sun	2020	Integrating Dijkstra's algorithm into deep inverse reinforcement learning for food delivery route planning	Transportation Research Part
6	Zhu, Yulun Zhang, Gui Chu, Rong Xiao, Huashun Yang, Yongke Wu, Xin	2024	Research on escape route planning analysis in forest fire scenes based on the improved A* algorithm	Ecological Indicators
7	Bento, Lucila M.S. Boccardo, Davidson R.Machado, Raphael C.S. Miyazawa, Flávio K. Pereira de Sá, Vinícius G. Szwarcfiter, Jayme L	2019	Dijkstra graphs	Discrete Applied Mathematics
8	Jason Siever, Melvin Valentino, Alvin Suryaningrum, Kristien Margi Yunanda, Rezki	2022	Dijkstra's algorithm to find the nearest vaccine location	Procedia Computer Science
9	Rosita, Yesy Diah Rosyida, Erly Ekayanti Rudiyanto, Muhammad Adik	2019	Implementation of dijkstra algorithm and multi-criteria decision-making for optimal route distribution	Procedia Computer Science
10	Öztürk, Ülkü Akdağ, Melih Ayabakan, Tarık	2022	A review of path planning algorithms in maritime autonomous surface ships: Navigation safety perspective	Ocean engineering
11	Manel Grifoll, Clara Bor´en, Marcella Castells-Sanabra	2022	A Comprehensive ship weather routing system using CMEMS products and A* algorithm	Ocean engineering
12	Donghun Yu, Myung-Il Ro0068	2024	Method for anti-collision path planning using velocity obstacle and A* algorithms for maritime autonomous surface ship	International Journal of Naval Architecture and Ocean Engineering
13	V. Novac, E. Rusu	2022	Ship routing using A* algorithm – A black sea case study	Maritime Policy Management
14	M.A. Hinostroza, C. Guedes Soares	2021	Global and local path-planning algorithm for marine autonomous surface ships including forecasting information	Maritime Technology and Engineering
15	Chanhee Seo, Yoojeong Noh, Misganaw Abebe, Young-Jin Kang, Sunyoung Park, Cheolhyeon Kwon	2023	Ship collision avoidance route planning using CRI-based A* algorithm	International Journal of Naval Architecture and Ocean Engineering
16	Trung Tien Tran, Thomas Browne, Mashrura Musharraf, Brian Veitch	2023	Pathfinding and optimization for vessels in ice: A literature review	Cold Regions Science and Technology
17	Andreas Breivik Ormevik, Kjetil Fagerholt, Frank Meisel, Endre Sandvik	2023	A high-fidelity approach to modeling weather-dependent fuel consumption on ship routes with speed optimization	Maritime Transport Research.
18	Renan Guedes Maidana, Susanna Dybwad Kristensen, Ingrid Bouwer Utne, Asgeir Johan Sørensen	2023	Risk-based path planning for preventing collisions and groundings of maritime autonomous surface ships	Ocean engineering
19	Zilong Guo, Mei Hong, Yongchui Zhang, Jian Shi, Longxia Qian, dan Hanlin Li.	2024	Research on safety evaluation and weather routing optimization of ship based on roll dynamics and improved A* algorithm,	-
20	Xianming Zhu, Hongbo Wang, Zihao Shen, Hongjun Lv	2016	Ship weather routing based on modified Dijkstra algorithm	6th International Conference on Machinery, Materials, Environment, Biotechnology and Computer (MMEBC 2016

3.2. Article Review

The summary of the findings from the completed article review is outlined in Table 3.

Table 3: Article review results based on RQs.

No	Referensi	RQ1	RQ2	RQ3	RQ4	RQ5
1	Optimal path planning in a real-world radioactive environment: A comparative study of A-star and Dijkstra algorithms	The implementation of algorithms such as Dijkstra and A-star in path planning enables effective navigation by considering factors such as radiation dose rate and the distance between nodes, which are crucial for making informed decisions in hazardous environments. Path planning contributes to the overall goal of optimizing radiation protection, ensuring that workers can perform their tasks while minimizing the risk of radiation exposure.	This study employs Dijkstra and A-star algorithms for efficient path planning in radioactive environments. The algorithms utilize heuristic values derived from gamma dose rates to optimize the pathfinding process. The Radiation Detection Backpack System (RDBS) is used to measure gamma radiation, aiding in determining the optimal path while minimizing radiation exposure.	-	-	Experimental results indicate that using radiation dose as the cost in the Dijkstra algorithm is more effective in minimizing exposure compared to using only the distance between nodes. Overall, applying this algorithm enhances safety and effectiveness in navigating hazardous environments by providing an optimal path that takes both distance and radiation levels into account.
2	A Three-Dimensional Dijkstra's algorithm for multi-objective ship voyage optimization	Path planning is essential for proposing a ship's sailing route from the departure port to the destination port while achieving predefined objectives, such as minimizing fuel consumption and air emissions. This enables route optimization based on sea weather forecasts, vessel characteristics, and operational capabilities, ensuring efficient navigation.	The proposed Three-Dimensional Dijkstra Algorithm (3DDA) enables efficient path planning by producing a globally optimal solution for ship routes, focusing on minimizing fuel consumption and other objectives such as damage accumulation and crack propagation. The 3DDA method incorporates voluntary speed adjustments based on sea conditions, allowing for speed reduction during rough weather to exponentially reduce fuel consumption.	The proposed 3D Dijkstra algorithm for ship route optimization has certain limitations, including the requirement for high computational effort to generate the 3D weighted graph, which involves creating a waypoint grid and extracting metocean environmental data. Safety-related factors, such as avoiding harsh sea conditions, are also treated as constraints, which can limit the flexibility of route planning.	proposed Three-Dimensional Dijkstra Algorithm (3DDA) is designed to optimize ship routes by considering multiple objectives, such as minimizing fuel consumption and damage accumulation, thereby enhancing maritime navigation efficiency.	The use of the Three-Dimensional Dijkstra Algorithm (3DDA) enables the generation of globally optimal solutions for ship routes, potentially leading to significant fuel savings compared to conventional methods. This is demonstrated by a reduction of at least 5% in fuel consumption in the analyzed cases.
3	Dynamic anti-collision A-star algorithm for multi-ship encounter situations	Path planning is essential to ensure safe navigation and collision avoidance in complex multi-ship encounter scenarios. It aids in generating feasible routes that take into account both dynamic and static obstacles, balancing navigational risk and economic efficiency. The implementation of path planning algorithms, such as	The research paper proposes the Dynamic Anti-collision A-star (DAA-Star) algorithm for efficient path planning in complex multi-ship encounter scenarios. This algorithm is based on the traditional A-star algorithm and incorporates maritime navigation rules. The DAA-Star algorithm features a dynamic search	he integration of ship path planning and actual control is not considered in the study, which limits the effectiveness of the strategy in real-world applications. The precise timing required to follow the path is not accounted for when using a dynamic ship model, which may lead to inaccuracies in navigation.	The DAA-Star algorithm demonstrates improved efficiency in generating navigation paths compared to traditional algorithms, especially in complex multi-ship encounter scenarios. It effectively balances navigational risk and economic efficiency. Simulation results show that the DAA-Star algorithm can produce more feasible routes for	The use of the DAA-Star algorithm enables dynamic collision avoidance in complex multi-ship encounter scenarios, which cannot be achieved with traditional algorithms. The DAA-Star algorithm integrates time factors and ship maneuverability constraints, enhancing safety and efficiency in path planning compared

		the DAA-Star algorithm, is crucial for complying with maritime regulations and ensuring the safety of vessels at sea.	mechanism that takes time factors into account, enabling collision avoidance for known moving obstacles.		avoiding both dynamic and static obstacles, which is critical for maritime navigation.	to methods that do not consider these elements.
4	Improved Dijkstra Algorithm for Mobile Robot Path Planning and Obstacle Avoidance	Path planning is essential to ensure that mobile robots can navigate from a starting point to a target while avoiding obstacles in their environment. This is crucial for safe and efficient robot operation. It enables route optimization, minimizing both the distance traveled and the time required to reach the destination.	The research paper discusses an enhanced Dijkstra algorithm as a strategy for efficient path planning in mobile robots, particularly for obstacle avoidance. The algorithm operates by modeling the environment as a digraph, where nodes represent positions and edges represent paths with associated weights.	-	-	The use of algorithms like the enhanced Dijkstra algorithm enables optimal path planning and obstacle avoidance for mobile robots, which is crucial for efficient navigation in complex environments. Without such algorithms, mobile robots may struggle to determine the best route to take, potentially leading to inefficient paths or collisions with obstacles.
5	Integrating Dijkstra's algorithm into deep inverse reinforcement learning for food delivery route planning	Path planning is essential due to the rapid growth of online food delivery, which generates a high volume of orders relying on efficient routes for couriers using electric bicycles. Actual delivery routes often differ from the system-recommended paths, necessitating reliable methods to determine the optimal route.	This study utilizes Deep Inverse Reinforcement Learning (IRL) algorithms to capture courier preferences from historical GPS trajectories, helping to recommend their preferred routes. The Dijkstra algorithm is integrated into the approach to determine current policies and calculate IRL gradients, enhancing the efficiency of path planning.	-	-	The use of the Dijkstra algorithm in the proposed model enables accurate determination of current policies and gradient calculation within the deep inverse reinforcement learning framework, which is crucial for effective route planning. By employing the Dijkstra algorithm, the model can provide better delivery route recommendations based on historical GPS trajectories, leading to improved alignment with courier preferences.
6	Research on escape route planning analysis in forest fire scenes based on the improved A* algorithm	Path planning becomes absolutely vital in emergency situations like wildfires. Effective path planning not only enhances the efficiency of route selection but also boosts safety, dynamically assesses risks, and ultimately helps reduce casualties during wildfire incidents.	Using a refined A* algorithm to enhance the efficiency of path planning in wildfire conditions. The algorithm is employed to search for escape routes to the nearest safe areas and calculate appropriate evacuation paths in real-time, thereby improving escape safety.	-	-	The use of an enhanced A* algorithm for escape route planning during wildfires can significantly improve the efficiency and safety of evacuation paths compared to not using any algorithm. Without such an algorithm, escape routes tend to be suboptimal, potentially leading to longer and more hazardous paths.

7	Dijkstra graphs	In the context of structured programming, path planning is a crucial aspect of algorithm design. Path planning helps identify the most efficient route for executing an algorithm.	Using the efficient Dijkstra algorithm to introduce programming in a structured way, enabling its application to a variety of real-world problems.	-	-	The use of this algorithm can enhance the efficiency of decision-making processes related to program structure. Compared to not using an algorithm, determining whether a program is structured can become more complex and time-consuming, often requiring manual analysis or less efficient methods.
8	Dijkstra's algorithm to find the nearest vaccine location	Path planning is crucial for locating vaccines to ensure quick and efficient access to vaccination sites. Effective path planning can also reduce travel time, fuel consumption, and transportation costs.	The Dijkstra algorithm is a strategy used to determine efficient routes by finding the shortest path to the nearest vaccination site. The "current location" feature is also employed as a strategy to optimize the program's functionality for users.	-	-	The use of the Dijkstra algorithm can identify the shortest path to a destination, helping to produce more efficient navigation and reduce travel time for users. Without the algorithm, individuals may struggle to determine the most efficient route, resulting in longer travel times. Implementing this algorithm optimizes the program with a "current location search" feature. Without such an algorithm, users find it difficult to find routes, making it challenging to effectively visualize the path.
9	Implementation of dijkstra algorithm and multi-criteria decision-making for optimal route distribution	In logistics, path planning is essential because it plays a vital role in optimizing various operations. Path planning helps improve distribution efficiency by determining the fastest routes, saving costs, and reducing delivery times as well as overall logistics expenses.	The combination of the Dijkstra algorithm and Multi-Criteria Decision Making (MCDM) can enhance efficiency in path planning. Prioritizing various parameters such as cost, distance, congestion, and risk helps streamline the decision-making process. The Dijkstra algorithm is also highly effective in calculating the shortest path for route optimization.	-	-	With the presence of algorithms, route distribution efficiency will undoubtedly improve significantly. Without using an algorithm, the decision-making process becomes more complex and time-consuming.
10	A review of path planning algorithms in maritime autonomous surface ships: Navigation safety perspective	Path planning for Maritime Autonomous Surface Ships (MASS) is crucial because it ensures safe, efficient, and	The use of path planning algorithms serves as a crucial tool in autonomous maritime vehicle navigation, where the calibration of safe	Ship route planning faces a myriad of obstacles—traps, safety concerns, complexity, and the ever-changing dynamics of the	Efficiency in maritime navigation pathfinding hinges critically on the ability to manage safety and environmental complexity.	The use of algorithms can significantly enhance navigation safety by ensuring compliance with collision regulations

		regulation-compliant vessel operations in a dynamic marine environment. Path planning is essential to avoid collisions, comply with international regulations, and adapt to the ever-changing conditions at sea, thereby supporting safe and effective maritime operations.	distances and speeds can be tailored to comply with stringent regulatory amendments. Ant Colony Optimization (ACO) acts as an intelligent strategy that can be combined with other algorithms, creating a harmonious approach to avoiding both local and global obstacles. This combination not only enhances efficiency but also crafts optimal routes that conquer the uncertainties of the sea, guiding autonomous vehicles through perilous twists and turns with confidence and resilience.	maritime environment—that challenge the creation of a reliable autonomous system. Traffic regulations on waterways demand careful integration within planning algorithms to respect legal boundaries and ensure compliance. A critical limitation lies in the reliance on algorithms that do not fully account for dynamic environmental factors like wind, waves, and currents, leaving gaps in maritime navigation strategies and risking suboptimal or unsafe routing.	Algorithms like Ant Colony Optimization (ACO) and Rapidly-Exploring Random Tree (RRT) bring innovative approaches—ACO excels in collision avoidance when combined with other methods. Therefore, performance metric analysis is essential to identify the fastest and safest routes. Calibrating safe distances and speeds enhances compliance with maritime regulations, while Velocity Obstacle (VO) techniques offer more efficient dynamic hazard avoidance, adapting swiftly to moving threats on the water.	(COLREG) and improving route efficiency. Without such pathfinding algorithms, the planning process loses accuracy and the adaptability needed to respond to the complex and dynamic maritime environment, increasing the risk of collisions and navigational errors. Algorithms are the vigilant guardians in this chaotic sea, turning uncertainty into calculated certainty, steering vessels away from disaster with precision and foresight.
11	A Comprehensive shipweather routing system using CMEMS products and A* algorithm	Path planning is essential to optimize sailing routes by considering various factors such as wave actions, ship emissions, and safety during navigation. This approach helps minimize the distance traveled and the time required for the journey, leading to significant reductions in fuel consumption and lower emissions. In the vast, restless ocean, path planning becomes the silent navigator—charting not just the shortest path, but the wisest one, balancing nature's forces with the imperative of sustainability.	The A* pathfinding algorithm is utilized in the SIMROUTE software to optimize sailing routes by accounting for wave actions. The methodology includes assessing safety constraints in accordance with the International Maritime Organization guidelines, which helps avoid hazardous waypoints during navigation. Like a vigilant guardian, this approach steers vessels through safer waters, weaving efficiency with compliance to safeguard lives and cargo alike.	The strategies used in maritime navigation pathfinding do not take into account crucial factors such as water depth, restricted areas, piracy threats, or territorial waters, all of which can significantly impact route optimization. The methodology applied in SIMROUTE relies on wave parameters from the Copernicus Marine Environment Monitoring Service (CMEMS), which may not always align perfectly with the specific conditions encountered during navigation. This gap leaves room for risk and inefficiency, underscoring the need for a more holistic and adaptive approach to truly master the unpredictable sea.	The A* pathfinding algorithm is used in the SIMROUTE software to efficiently optimize sailing routes with consideration of wave conditions. The accuracy of A* is validated by comparing the orthodromic (great-circle) distance, demonstrating that this algorithm can accurately calculate the shortest path. SIMROUTE's comprehensive structure facilitates easy modification and integration of ship wave resistance models, thereby enhancing flexibility and improving efficiency under varying maritime conditions.	The implementation of the A* pathfinding algorithm in the SIMROUTE software optimizes sailing routes based on wave action, enhancing the efficiency of ship weather routing. Without algorithms like A*, the routing process may fail to account for dynamic factors such as wave conditions, potentially leading to longer travel times and increased fuel consumption.
12	Method for anti-collision path planning using velocity obstacle and A* algorithms for maritime autonomous surface ship	Path planning is essential to ensure the safety of autonomous ship navigation, particularly in avoiding collisions with other vessels. * It addresses the critical risk of	The proposed method for efficient path planning is called VO-PATH, which combines the Velocity Obstacle (VO) algorithm and the A* algorithm to enhance collision avoidance	The Velocity Obstacle (VO) algorithm faces limitations when multiple obstacles are present, resulting in a limited set of feasible velocity choices. VO can become trapped in local minima, leading	This journal introduces a novel hybrid path planning method called VO-PATH, which combines the Velocity Obstacle and A* algorithms to enhance maritime navigation efficiency. A* serves as the path	The proposed VO-PATH algorithm enhances the collision avoidance capability for Maritime Autonomous Surface Ships (MASS) by integrating the Velocity Obstacle (VO) algorithm with

		collisions, which can have severe consequences, including loss of life and environmental damage. Effective path planning enhances the efficiency of anti-collision technologies, which are vital for the commercial viability of Maritime Autonomous Surface Ships (MASS). The proposed hybrid collision avoidance path planning method, VO-PATH, combines the strengths of existing algorithms to optimize routes while ensuring safety.	capabilities for autonomous ships. The VO algorithm is effective in collision avoidance due to its geometric simplicity and low computational demand, but it has limitations, such as a short-sighted focus on instantaneous situations.	to suboptimal decisions that may steer the vessel toward unavoidable collisions in the near future. Existing VO algorithms do not fully account for future situations from a global path perspective, which can cause inefficient evasive maneuvers and unnecessary course changes.	optimizer, effectively determining the safest and most efficient route by considering static obstacles and navigational rules. VO-PATH improves collision avoidance in complex multi-encounter scenarios, achieving up to a 6.6% efficiency gain compared to using conventional A* alone. This integration significantly boosts both navigational capability and efficiency in maritime path planning.	the A* algorithm, resulting in more efficient path planning. The VO algorithm alone has limitations, such as short-sighted focus on immediate situations, which can increase the risk of collisions in high-density vessel areas.
13	Ship routing using A* algorithm – A black sea case study	Path planning is essential to ensure safe navigation by avoiding hazards such as storms, ice fields, and obstacles in the maritime environment. It helps optimize routes to minimize costs and reduce air emissions while prioritizing the safety of the vessel and its crew. Effective path planning addresses the complexities of maritime navigation, including environmental conditions like wind, waves, and currents, which can significantly impact the voyage.	The A* algorithm is used for efficient path planning in ship routing because it balances route length and safety by minimizing a cost function. It enhances Dijkstra's algorithm by incorporating heuristics, which reduces computation time and the number of nodes explored during the search process. This improvement addresses routing problems by finding the optimal path more quickly and effectively, making it highly suitable for dynamic and complex maritime navigation scenarios.		The use of algorithms, particularly the A* algorithm, is highly efficient in finding the fastest maritime navigation routes by minimizing the cost functions associated with sailing. Algorithms like A* enhance traditional methods such as Dijkstra's algorithm by leveraging heuristics, which significantly reduce computation time and the number of nodes that need to be explored during the search process. The integration of accurate meteorological and oceanographic forecasts further boosts the effectiveness of this algorithm in ship routing, enabling better decision-making concerning both the safety and economic aspects of navigation.	Using algorithms like A* can lead to an optimal route between two ports, minimizing costs and reducing air emissions while prioritizing the safety of the ship and its crew. These algorithms assist the ship's captain in decision-making and enhance the operations of the navigation department on the bridge, bringing precision and efficiency to every voyage.
14	Global and local path-planning algorithm for marine autonomous surface ships including forecasting information	Path planning is essential to calculate the optimal route for autonomous surface vessels, especially in complex environments with dynamic and static obstacles. It ensures the vessel can navigate safely while avoiding collisions and shallow	The global path planning algorithm employs the Fast Marching Square method, enhanced by incorporating forecast data to calculate more realistic routes. The local path planning algorithm uses a guided Fast Marching Square	The research paper does not explicitly mention the limitations of the strategies used in maritime navigation pathfinding. It focuses on the development of global and local path planning algorithms for autonomous surface vessels but does not detail	The research paper presents a novel approach to global and local path planning for autonomous surface vehicles, incorporating algorithms to compute optimal routes for maritime navigation. The global path planning algorithm is validated	The use of algorithms such as the fast-marching square method enables the calculation of optimal routes over large areas by taking into account various factors like weather forecasts and vessel responses to waves. This results in more realistic and efficient

		waters, which are impractical for marine vehicles. Incorporating forecast data into path planning enhances the realism and effectiveness of the calculated routes, enabling better decision-making in navigation.	approach to navigate through small, complex areas with dynamic and static obstacles. Computational analysis indicates that a 100x100 map grid is the optimal choice for real-time path planning.	specific constraints or drawbacks of these strategies.	in realistic scenarios, demonstrating strong performance in identifying efficient navigation routes. The integration of forecast data into the fast marching square method enhances the realism and efficiency of the calculated paths, making the algorithm more effective for maritime navigation.	path planning for autonomous surface vessels. Without employing such algorithms, the resulting routes may be dangerously close to obstacles, which is impractical for autonomous surface vehicles—especially in shallow waters. This can lead to unsafe navigation conditions.
15	Ship collision avoidance route planning using CRI-based A* algorithm	Path planning is not merely about calculating a route—it is an art of weaving through the waves of risk and safety. By integrating the Collision Risk Index (CRI), which evaluates DCPA and TCPA, the navigation system can sense danger before it becomes a real threat. The CRI-based A* algorithm acts not only as a pathfinder but as an adaptive guardian, charting a course that is economically efficient while strictly adhering to COLregs, the lifeblood of maritime navigation. With this strategy, the total distance traveled can be reduced without compromising safety, moving beyond conventional approaches that often oversimplify and overlook the complexity of collision risks. Operational safety is elevated to a new level—a symphony of harmony between algorithmic sophistication and the harsh demands of the ever-changing sea. The route is no longer just a path; it becomes a shield and guide through an unforgiving ocean.	Algoritma A* berbasis Cri yang diusulkan mengintegrasikan strategi penghindaran tabrakan dengan perencanaan rute untuk meningkatkan keselamatan dan ekonomi operasional. Algoritma mendefinisikan zona penalti berdasarkan kapal target untuk memastikan kepatuhan terhadap Peraturan Internasional untuk Mencegah Tabrakan di Laut (COLregs). Ini mengevaluasi Indeks Risiko Tabrakan (CRI) dengan mempertimbangkan beberapa faktor seperti Jarak Titik Pendekatan Terdekat (DCPA), Titik Pendekatan Waktu Terdekat (TCPA), jarak relatif, sudut relatif, dan kecepatan relatif. Algoritma melakukan pencarian simpul adaptif pada grid peta lokal yang disesuaikan dengan berbagai situasi pertemuan, memungkinkan eksplorasi rute aman yang efisien. Proses pencarian dioptimalkan dengan memeriksa pelanggaran nilai CRI dan ColRegs di setiap node, memastikan bahwa biaya jalur diminimalkan sambil menjaga keamanan. Metode ini telah divalidasi melalui simulasi ekstensif di berbagai skenario	-	The proposed CRI-based A* algorithm demonstrates notable efficiency in maritime navigation by seamlessly integrating safety and operational economy, which are critical for effective route planning. This algorithm effectively evaluates the Collision Risk Index (CRI) to identify safe routes while accounting for various encounter scenarios, leading to the discovery of optimal paths. Compared to traditional ship domain-based methods, the CRI-based A* algorithm has proven its superior capability in maintaining low collision risk while exploring economically efficient routes. Simulations validate that the proposed method can generate routes that avoid collision risks while achieving equal or shorter distances compared to other models, thereby enhancing overall path efficiency.	The proposed CRI-based A* algorithm integrates collision avoidance measures, significantly enhancing safety during ship navigation compared to traditional methods that do not employ such algorithms. Without this algorithm, vessels often rely on distance-based models like Goodwin and Fujii, which may produce shorter routes but at the expense of increased collision risk. The CRI-based algorithm maintains the maximum CRI value below 0.7, ensuring both safety and efficiency, whereas conventional models can exceed this threshold, indicating a higher collision risk. This algorithm enables adaptive and effective node searching based on various encounter scenarios, improving route planning and collision avoidance beyond non-algorithmic approaches. Overall, the use of the CRI-based A* algorithm results in a more robust and economically viable route planning method, while traditional methods risk compromising safety for efficiency.

			pertemuan, menunjukkan efektivitasnya dalam mengeksplorasi rute ekonomis sambil meminimalkan risiko tabrakan.			
16	Pathfinding and optimization for vessels in ice: A literature review	Route planning is essential to ensure safe navigation through ice-covered waters while complying with maritime regulations. It optimizes maritime voyages by balancing economic and environmental factors, which are crucial for efficient operations. The objectives of route optimization typically include minimizing travel distance, voyage time, and fuel consumption—key elements for cost-effective navigation. Effective route planning takes into account operational constraints posed by ice conditions, which can significantly impact ship performance and safety. The dynamic nature of the ice environment demands adaptive route planning that accounts for changing conditions, thereby enhancing the reliability of routing tools.	The literature review identifies several optimization techniques used for efficient route planning in ice-covered waters, with graph-based methods—including the A* and Dijkstra algorithms—being the most dominant, utilized in over half of the reviewed studies. Other mentioned techniques include genetic algorithms, wavefront-based algorithms, ant colony optimization, stochastic dynamic programming, finite element methods, linear regression, and Powell's method. Scalarization methods are commonly applied, where weights are assigned to each operational objective, allowing for comparison of actions based on their cost. The Pareto front approach is also employed, ensuring that selected routes are not inferior to others in any objective. The review highlights that future research should explore more operational constraints and incorporate validation techniques to enhance the reliability and practicality of routing tools.	This literature review does not explicitly outline the limitations of the strategies used in maritime navigation pathfinding. Instead, it focuses on summarizing existing literature and identifying research gaps rather than detailing specific shortcomings of the employed strategies. The study emphasizes the need for future research to explore more operational constraints and address uncertainties in route planning for vessels navigating ice-covered waters. It also highlights that validation techniques should be considered to enhance the reliability and practicality of routing tools, indicating potential limitations in current validation practices.	Optimization algorithms are the heartbeat of any pathfinding system, transforming raw input data into the best possible route within defined constraints and optimized objectives. Graph-based methods, such as the A* and Dijkstra algorithms, stand as the most popular techniques for route optimization, efficiently searching for paths by converting maps into discrete grid worlds. These graph-based algorithms can solve optimization problems in linear time relative to the number of edges and nodes, offering a powerful balance between speed and accuracy. Yet, this power comes with limits: graph-based methods demand a known, static graph that remains unchanged during the search process. This rigidity can be a bottleneck in dynamic or unpredictable maritime environments. On the other hand, wave-based algorithms skip the need for map discretization and produce smoother route suggestions, though often at the cost of increased computational expense due to handling a larger number of reference points. The choice of algorithm shapes the efficiency and effectiveness of finding the fastest maritime navigation route—each approach brings its own mix of strengths and weaknesses,	-

					depending on the specific challenges and priorities of the study at hand.	
17	A high-fidelity approach to modeling weather-dependent fuel consumption on ship routes with speed optimization	-	This study explores two speed optimization strategies—HiFID and FSL—applied to efficient route planning in maritime transportation. The HiFID approach is specifically designed to achieve lower fuel consumption compared to the FSL method, demonstrating its superior efficiency in route optimization. The research highlights the critical importance of modeling weather impacts on fuel consumption with higher levels of detail, as this significantly influences routing decisions and enhances the overall efficiency of path planning. A recursive smoothing algorithm is proposed to address the speed optimization problem, helping to maintain an average speed close to the most fuel-efficient speed throughout the voyage, thereby optimizing the route. Additionally, the study emphasizes the necessity of shortest-path solution approaches when weather conditions affect fuel consumption, further supporting the creation of efficient and adaptive maritime navigation plans.	The strategies used in maritime navigation pathfinding may oversimplify the impact of weather conditions, failing to capture the complex interactions among various weather factors and their influence on fuel consumption and speed optimization. The proposed recursive smoothing algorithm for speed optimization is only applicable when the fuel consumption function is convex and remains constant throughout the route—an assumption that often does not hold true in real-world scenarios where weather conditions fluctuate. Common approaches to modeling weather effects tend to misestimate the actual costs of traveling under realistic weather, exposing limitations in accurately predicting fuel consumption. Model fidelity—the level of detail in representing weather impacts—can significantly affect routing decisions, indicating that a lack of precision may lead to suboptimal routing and increased fuel consumption. In essence, without embracing the chaotic nuance of nature's forces, these simplified models risk steering ships onto paths less efficient, less safe, and more costly than they need to be.	-	-

18	Risk-based path planning for preventing collisions and groundings of maritime autonomous surface ships	Path planning is necessary to generate risk-acceptable trajectories for autonomous surface ships, ensuring safe navigation in dynamic environments. It allows for the evaluation of multiple paths, enabling operators to choose how strict the autonomous ship's decision-making should be regarding risk, thus avoiding overly conservative minimization algorithms.	The method for efficient path planning involves a two-step process using K-shortest-paths Probabilistic Risk Assessment (KPRA) alongside risk models and dynamic system simulation. This generates a list of paths ranked by risk. Multiple risk influencing factors and accident types, such as collision and powered grounding accidents, are considered in the path planning process.	The research does not explicitly outline the limitations of the strategy used in the search for maritime navigation lanes. However, it suggests that the assumptions made during experiments, such as the trajectory of the target ship (TS) and the constant global wind, may limit the applicability of the findings in dynamic real-world scenarios.	The research paper discusses the efficiency of the K-shortest-paths Probabilistic Risk Assessment (KPRA) method in generating risk-acceptable trajectories for autonomous surface ships, which can be seen as a form of algorithmic path planning. The integration of KPRA allows for the evaluation of multiple paths, enabling operators to choose how strict the autonomous ship's decision-making should be regarding risk, which can lead to more efficient navigation decisions.	The use of the K-shortest-paths Probabilistic Risk Assessment (KPRA) algorithm allows for the generation of risk-acceptable trajectories for an autonomous surface ship, which is not possible without it. This method evaluates multiple paths and ranks them based on risk, enabling operators to make informed decisions regarding the ship's navigation.
19	Research on safety evaluation and weather routing optimization of ship based on roll dynamics and improved A* algorithm,	Path planning is necessary to ensure safe navigation for ships, particularly in the context of maritime accidents and environmental challenges. It helps in calculating the safest and fastest return path to port, which is crucial for minimizing risks during navigation. The A* algorithm is employed in path	The A* algorithm is employed as an effective and direct method for solving the shortest path problem in a static environment. The algorithm utilizes a cost function that combines the cost from the initial node to the current node and an estimated cost from the current node to the target node.	The study acknowledges limitations in terms of data availability, which can impact the accuracy of the models used for maritime navigation safety. There is a noted gap in understanding the dynamics of ship stability under various environmental conditions, which may affect the effectiveness of the navigation strategy.	The A* algorithm is identified as the most effective and direct method for solving the shortest path problem in a static environment, which is crucial for maritime navigation. The efficiency of the A* algorithm lies in its ability to calculate the cost function from the initial node to the target node, optimizing the search for the fastest maritime navigation path.	The use of an algorithm, such as the A* algorithm, allows for the planning of a path that considers not only the distance but also evaluates risk and time costs, which can lead to a safer and more efficient route. Without using an algorithm, the path planning may not account for these critical factors, potentially resulting in longer sailing times and increased exposure to high-risk sea areas.
20	Ship weather routing based on modified Dijkstra algorithm	Path planning is necessary for optimizing ship routing, which involves determining the shortest time path or the most economical path while considering weather conditions. It helps in minimizing various factors such as passage time, fuel consumption, and structural damage to the ship.	The modified Dijkstra algorithm is utilized for efficient path planning by employing a structure matrix and a single linked list, which enhances computational efficiency. The use of a structure matrix instead of an adjacency matrix helps save storage space, while the single linked list reduces time consumption during the algorithm's execution.		The modified Dijkstra algorithm demonstrates improved efficiency in searching for the fastest maritime navigation path by utilizing a structure matrix and a single linked list, which reduces time consumption and storage needs. The algorithm's computational complexity is enhanced, allowing it to handle a larger number of vertices more effectively, which is crucial for maritime routing.	The use of the modified Dijkstra algorithm improves computational efficiency compared to traditional methods, allowing for faster route optimization in ship weather routing. Without the algorithm, finding the shortest or most economical path considering weather conditions would be significantly more time-consuming and less efficient.

3.3. Answering Research Question

To comprehensively address the questions, each research question will be discussed in detail one by one.

3.3.1. Answering RQ 1

Path planning is a critical component in various fields, including robotics, maritime navigation, and transportation, due to its role in optimizing routes and ensuring safety. In the context of mobile robots (MR), path planning is essential for navigating environments with obstacles, ensuring that the MR follows the shortest path while avoiding collisions. This is achieved through algorithms like Dijkstra's, which efficiently find the optimal path from a starting point to a target point in a graph-based model of the environment [12]. Similarly, in maritime navigation, path planning is crucial for weather routing and speed optimization, where it helps in minimizing fuel consumption and avoiding hazardous conditions like severe storms or ice, thus ensuring the safety and efficiency of voyages [13]. In ice-covered waters, path planning is necessary to optimize routes based on objectives such as voyage distance, time, and fuel consumption, while also considering dynamic environmental changes and operational constraints [14].

The use of graph-based algorithms in these scenarios highlights the importance of path planning in adapting to changing conditions and optimizing performance. Furthermore, in complex environments like radioactive areas, path planning is vital for determining safe and efficient routes, with algorithms like A-star and Dijkstra being employed to navigate these challenging settings [11]. The necessity of path planning is underscored by its ability to provide optimal solutions in diverse applications, from ensuring the shortest and safest paths in robotics to optimizing maritime routes under varying environmental conditions. This multifaceted utility demonstrates why path planning is indispensable across different domains, as it enhances operational efficiency, safety, and adaptability to dynamic environments.

3.3.2. Answering RQ 2

Efficient path planning strategies are crucial in various applications, including mobile robotics and navigation in complex environments. One widely used approach is the graph-based method, which involves converting a map into a discretized grid where each cell acts as a node, and connections between cells form edges. This method allows the use of algorithms like A* and Dijkstra's to find the optimal path by minimizing the cost function associated with traversing nodes [14]. Dijkstra's algorithm, in particular, is noted for its simplicity and effectiveness in finding the shortest path in static environments, as it can operate without adding extra nodes, thus avoiding additional computational burdens [12]. It is also capable of dynamically updating paths in response to moving obstacles, making it suitable for real-time applications [12].

In radioactive environments, path planning strategies incorporate radiation dose calculations to ensure safety, using algorithms like A* and Dijkstra's to determine paths that minimize exposure [11]. Additionally, wave-based methods offer an alternative by directly using vector formats of environmental data, such as ice charts, to generate smoother routes, although they can be computationally intensive due to the increasing number of reference points [14]. Moreover, the integration of neural dynamics and machine learning techniques, such as Q-learning, has been explored to enhance path planning in dynamic and unknown environments, although these methods may require significant computational resources [12]. Validation of these strategies is essential, and methods range from field tests to simulations and expert consultations, ensuring that the path planning systems are reliable and effective in real-world scenarios [14]. Overall, the choice of strategy depends on the specific requirements of the application, such as the need for real-time updates, computational efficiency, and the complexity of the environment.

3.3.3. Answering RQ 3

The search for maritime navigation lanes involves several strategies, each with its own limitations. One significant limitation is the reliance on historical AIS data for route validation, which assumes that past routes are optimal and that navigators performed perfectly. This assumption can lead to inaccuracies if the historical routes were suboptimal due to unforeseen conditions or human error [14]. Additionally, the use of velocity obstacle (VO) algorithms in path planning, while effective for avoiding collisions, is limited by its focus on current scenarios without adequately predicting future collision risks. This can result in suboptimal path choices, especially in dynamic environments with multiple obstacles [15]. Furthermore, the A-star algorithm, commonly used in path planning, may not account for the maneuverability restrictions of ships, leading to paths that are difficult to follow due to unrealistic turning radii [3].

Another limitation is the potential for planned paths to be too close to obstacles, which is particularly problematic for autonomous surface vehicles (ASVs) navigating shallow waters. This issue necessitates the use of algorithms like the fast-marching square (FMS) method to maintain a safe distance from obstacles [16]. Moreover, the integration of real-time environmental data, such as weather conditions, is often limited, which can affect the accuracy and safety of the planned routes [16]. These limitations highlight the need for more comprehensive models that incorporate dynamic environmental factors, ship-specific constraints, and advanced validation techniques to improve the reliability and safety of maritime navigation lane strategies.

3.3.4. Answering RQ 4

The use of algorithms in maritime navigation, particularly for finding the fastest path, has shown significant efficiency and potential for optimization. The A* algorithm, for instance, is highlighted as a highly effective method for solving the shortest path problem in static environments, offering rapid response to environmental changes and direct path searching capabilities [17]. This algorithm has been applied in various maritime scenarios, including a Black Sea case study, where it demonstrated improvements in planned path length and time of passage, albeit with modest reductions in distance and negligible impacts on fuel consumption and emissions [6]. The A* algorithm's efficiency is further enhanced by incorporating International Maritime Organization (IMO) restriction rules, which help in planning paths that avoid risks and reduce sailing time, ensuring safe and efficient navigation [17].

Additionally, the integration of risk zoning maps and weather forecasting models can further refine the algorithm's precision, making it a valuable tool for shipmasters in decision-making processes [6], [17]. Other studies have explored the use of algorithms like the fast marching square method and COLREG-compliant algorithms, which consider both static and dynamic obstacles, to generate smooth and viable trajectories that adhere to maritime regulations [5]. These algorithms are designed to maintain a safe distance from obstacles while optimizing path efficiency, demonstrating their capability to handle complex maritime environments. The efficiency of these algorithms is also evident in their ability to simulate various encounter situations and operation conditions, providing reliable and safe navigation paths [18]. Overall, the use of algorithms in maritime navigation not only enhances the speed and safety of maritime routes but also contributes to environmental protection by optimizing fuel consumption and reducing emissions, making them an indispensable tool in modern maritime operations [6], [17], [19].

3.3.5. Answering RQ 5

The use of algorithms can significantly impact the effectiveness and safety of various operations, as demonstrated in different contexts. For instance, in the realm of forest fire escape planning, the traditional A* algorithm was found to be less effective because it plotted routes that were dangerously close to high-risk fire areas. In contrast, an improved version of the A* algorithm optimized these routes, ensuring that escapees maintained a safe distance from hazardous zones, thereby enhancing safety and applicability in real-world scenarios [20]. Similarly, in maritime navigation, the A* algorithm plays a crucial role in optimizing ship routes across the Black Sea. It helps in minimizing costs and reducing air emissions while prioritizing the safety of the ship and crew. This is particularly important given the environmental sensitivity of the Black Sea and the potential for naval disasters that can result in significant economic and environmental damage [20]. Furthermore, the application of algorithms in ship operations can mitigate the negative effects of ship motions, such as excessive roll and lateral accelerations, which can compromise safety and operational effectiveness. By addressing these issues, algorithms contribute to maintaining the stability of cargo and the performance of personnel on board [16]. In contrast, the absence of algorithmic planning could lead to inefficient routes, increased operational costs, and heightened safety risks. Additionally, the relevance of algorithms in adhering to maritime regulations, such as COLREG, is highlighted, with some algorithms being more adaptable than others. This adaptability is crucial for ensuring compliance and safety in maritime operations [19]. Overall, the use of algorithms in these contexts underscores their importance in enhancing safety, efficiency, and compliance, while their absence could lead to increased risks and inefficiencies.

4. Conclusion

The study on the performance analysis of Dijkstra and A* algorithms in maritime navigation pathfinding offers profound insights into their application and effectiveness. It underscores the critical importance of integrating advanced algorithms to enhance both the efficiency and safety of route planning and decision-making processes within the maritime domain. This research highlights the pivotal role of COLREG (Collision Regulations) in designing collision avoidance algorithms for Maritime Autonomous Surface Ships (MASS), identifying existing gaps in current path planning algorithms—particularly in adhering to specific COLREG rules essential for safe and efficient navigation.

Furthermore, the study demonstrates the versatility and efficacy of A* and Dijkstra algorithms in hazardous environments, such as radiation-emitting slag disposal sites. By incorporating radiation dose costs into weighted graphs, these algorithms can improve worker safety and optimize navigation routes. The research also emphasizes the need for future studies to refine these algorithms further and explore their applications across diverse real-world scenarios. More extensive field experiments are necessary to validate the effectiveness of these algorithms in contexts such as maritime navigation and logistics distribution.

In conclusion, the performance analysis of Dijkstra and A* algorithms in maritime pathfinding highlights their crucial role in route optimization, safety enhancement, and adaptability to complex, dynamic environments. These algorithms continue to evolve, integrating new factors and technologies to boost their effectiveness in maritime applications.

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