Path Planning Techniques for Underwater Robots Based on Obstacles in Subsea Oil Pipelines

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Abstract: With the continuous growth of global energy demand, the safety and maintenance of underwater oil pipelines have become a focal point of international concern. Autonomous Underwater Vehicles (AUVs) are increasingly pivotal in inspection, maintenance, and repair of oil pipelines. This paper explores path planning techniques for underwater robots based on obstacles in subsea oil pipelines to enhance operational efficiency and safety. Employing theoretical analysis and simulation, the study systematically addresses key issues in path planning, including environmental modeling, obstacle recognition, path generation, and optimization. By constructing complex underwater environment models and integrating advanced algorithms such as improved ant colony optimization, genetic algorithms, and particle swarm optimization, the research investigates path planning strategies for AUVs under various obstacle distributions. The results demonstrate that the proposed path planning techniques effectively handle obstacles in subsea oil pipelines, significantly improving planning efficiency and robustness. Additionally, the feasibility of multi-robot collaborative path planning is discussed, providing theoretical support for future advancements in underwater robotics. Overall, this study offers new technological insights for the maintenance of underwater oil pipelines and is crucial for enhancing the intelligence level of underwater operations.

Keywords: Underwater Robots; Path Planning; Oil Pipelines; Obstacle Recognition; Algorithm Optimization

1. Introduction

With the escalating global energy demand, the safety and maintenance of underwater oil pipelines have garnered international attention. Autonomous Underwater Vehicles (AUVs) play an increasingly critical role in the inspection, maintenance, and repair of oil pipelines. The study of path planning techniques for underwater robots is not only crucial for the efficiency and safety of underwater operations but also key to the efficient development of marine resources and environmental protection. Therefore, in-depth research on path planning for underwater robots based on obstacles in subsea oil pipelines is significant for advancing marine technology and ensuring national energy security.

Domestic research on underwater robot path planning started later but has rapidly progressed, particularly in algorithm optimization and practical applications. Algorithm Optimization: Chinese scholars have improved traditional algorithms such as ant colony optimization, genetic algorithms, and particle swarm optimization to meet the demands of complex underwater environments. For instance, Hu Hui [1] and Fu Lele et al. [3] have respectively enhanced ant colony algorithms, improving path planning efficiency and robustness. Multi-Robot Collaboration: Li Dongzheng et al. [5] studied collaborative path planning for multiple underwater robots based on a master-slave structure, achieving efficient cooperative operations in complex environments through distributed control strategies. Practical Applications: Cao Xiaoxu [10] addressed the practical needs of underwater pipeline inspection, researching coordination planning and control technologies for autonomous underwater robots, providing technical support for the safe inspection of underwater pipelines.

Abroad, research on underwater robot path planning began earlier, with deep technical accumulation, particularly in algorithm innovation and system integration. Algorithm Innovation: Foreign scholars continuously explore new path planning algorithms, such as remote-controlled underwater robot path planning based on improved A* algorithms [12], and underwater robot path planning based on optimized sparrow search algorithms [14], which exhibit better adaptability and efficiency in complex underwater environments. System Integration: Foreign research not only focuses on the path planning of single robots but also emphasizes multi-sensor information fusion and system integration. Leng Fang et al. [13] studied an underwater robot navigation system based on multi-sensor information collection, enhancing the navigation accuracy of robots in complex underwater environments. Intelligent Control: Lyu Xi et al. [15] researched local path planning for intelligent underwater robots based on deep deterministic policy gradient algorithms, enabling robots to autonomously learn and adapt to dynamically changing underwater environments through reinforcement learning methods.

Currently, China is actively advancing its maritime power strategy, and the development of underwater robot technology is crucial for ensuring national maritime and energy security. The Two Sessions' spirit emphasizes technological innovation and high-quality development, and the research on underwater robot path planning technology reflects this spirit. Combining social hotspots such as marine environmental protection and marine resource development, the advancement of underwater robot technology will help enhance China's discourse and influence in global marine governance. In summary, both domestic and international research on underwater robot path planning technology has made significant progress, yet faces numerous challenges, such as adaptability to complex underwater environments and efficiency of multi-robot collaborative operations. Future research should further align with practical application needs, strengthen algorithm innovation and system integration, and propel underwater robot technology to a higher level, providing robust support for the implementation of China's maritime power strategy.

This study aims to explore path planning techniques for underwater robots based on obstacles in subsea oil pipelines, systematically analyzing key issues in underwater robot path planning through theoretical analysis and simulation, including environmental modeling, obstacle recognition, path generation, and optimization. The research contents mainly include: (1) Underwater environment modeling and obstacle recognition technology; (2) Path planning algorithms for underwater robots based on obstacles; (3) Optimization and evaluation of path planning algorithms; (4) Multi-robot collaborative path planning strategies. Through this research, it is expected to provide new technological insights for the maintenance of underwater oil pipelines and enhance the intelligence level of underwater operations.

2. Overview of Underwater Robot Path Planning Techniques

2.1 Development History of Underwater Robot Technology

The development of underwater robot technology has transitioned from remotely operated vehicles (ROVs) to autonomous underwater vehicles (AUVs). Early underwater robots relied heavily on manual remote control. With advancements in sensor and computer technology, AUVs have become a research hotspot. These autonomous robots can independently complete tasks such as path planning and obstacle avoidance, significantly improving the efficiency and safety of underwater operations. In recent years, the progress in artificial intelligence has further enhanced the intelligence level of underwater robots, providing strong support for the maintenance of underwater oil pipelines.

2.2 Basic Principles of Path Planning Technology

Path planning technology is the core of autonomous operations for underwater robots. The basic principle involves finding an optimal path from a starting point to an endpoint within a given environment while avoiding obstacles. Path planning algorithms typically include global path planning and local path planning. Global path planning addresses the overall path from start to finish, while local path planning focuses on real-time collision avoidance and path optimization. Common path planning algorithms include the A* algorithm, Dijkstra's algorithm, genetic algorithms, and ant colony optimization. Each algorithm has its strengths and weaknesses, suitable for different application scenarios.

2.3 Challenges and Requirements in Underwater Robot Path Planning

Path planning for underwater robots faces numerous challenges. Firstly, the underwater environment is complex and dynamic, with uncertainties and changes such as currents, temperature, and lighting affecting path planning accuracy. Secondly, various types of obstacles, including seafloor topography, shipwrecks, and fishing nets, pose significant challenges for recognition and avoidance. Additionally, underwater robots have limited energy and computational resources, making efficient path planning crucial. Therefore, continuous innovation and optimization of path planning technology are necessary to meet practical application needs.

3. Underwater Environment Modeling and Obstacle Recognition

3.1 Analysis of Underwater Environment Characteristics

The underwater environment has unique physical and chemical characteristics that impose special requirements on path planning for underwater robots. Key features of the underwater environment include complex terrain, variable currents, limited lighting conditions, and diverse biological and non-biological obstacles. The seafloor features various geological structures like trenches, seamounts, and shipwrecks, which can interfere with robot movement and sensor operation. Current variations, including speed and direction, affect the robot's trajectory, complicating path planning. Limited lighting, especially in deep-sea areas, poses challenges for visual sensors. The dynamic nature of biological obstacles such as fish schools and seaweed further adds to the complexity of path planning.

3.2 Obstacle Recognition Techniques

Obstacle recognition is a critical component of path planning for underwater robots. Current techniques primarily rely on sonar, LiDAR, and visual sensors. Sonar uses sound waves to detect obstacles by analyzing reflected signals, performing well in turbid waters but with lower resolution. LiDAR emits laser beams and receives reflections to construct 3D models, offering high resolution and precision but with limited range underwater. Visual sensors capture underwater images for obstacle identification using image processing techniques. They work well in clear waters but are less effective in turbid conditions. Recently, deep learning-based obstacle recognition has emerged, using neural networks to efficiently identify complex obstacles.

3.3 Environment Modeling Methods

Environment modeling is fundamental to path planning for underwater robots. Main methods include grid maps, topological maps, and hybrid maps. Grid maps divide the environment into grids, with each representing a specific area, indicating obstacle information by marking grid occupancy. Grid maps are intuitive and easy to implement but require significant storage and computational resources in large environments. Topological maps use nodes and edges to represent key locations and paths, suitable for large-scale environments but less detailed. Hybrid maps combine the advantages of grid and topological maps, using topological maps for key locations and grid maps for local areas, achieving efficient modeling. Recently, probabilistic graphical models have gained attention, incorporating probability information to better handle environmental uncertainties.

3.4 Challenges and Future Directions

Despite the advancements in underwater environment modeling and obstacle recognition, several challenges remain. One major challenge is the integration of multi-sensor data to enhance the robustness and accuracy of obstacle detection. Different sensors have their strengths and weaknesses, and combining their outputs can lead to more reliable obstacle recognition systems. For instance, integrating sonar data with visual sensor information can compensate for each other's limitations, especially in varying water conditions.

Another challenge is the computational efficiency of environment modeling techniques. As underwater robots often operate in real-time, the algorithms used for environment modeling must be optimized for quick processing. This includes developing more efficient data structures and algorithms that can handle large datasets without compromising on speed.

Future research should also focus on improving the adaptability of underwater robots to dynamic environmental changes. This includes developing algorithms that can quickly update environment models based on real-time sensor data, allowing robots to adjust their paths dynamically in response to changes in the underwater landscape or biological activity.

Moreover, the application of advanced machine learning techniques, such as reinforcement learning, could be explored to enable underwater robots to learn from their environment and improve their path planning strategies over time. This approach could potentially lead to more autonomous and intelligent underwater robots capable of making decisions based on learned experiences.

In conclusion, while significant progress has been made in underwater environment modeling and obstacle recognition, ongoing research and development are crucial to address the remaining challenges. By leveraging advancements in sensor technology, computational methods, and machine learning, future underwater robots can be equipped with more sophisticated capabilities to navigate complex underwater environments safely and efficiently.

4. Path Planning Algorithms for Underwater Robots Based on Obstacles

4.1 Review of Traditional Path Planning Algorithms

Traditional path planning algorithms play a significant role in underwater robot path planning. The A* algorithm, a classic heuristic search algorithm, selects the path with the minimum cost by estimating the cost from the current node to the target node. A* offers good search efficiency and path quality but has high computational costs in complex environments. Dijkstra's algorithm, a graph-based shortest path algorithm, finds the shortest path from the start to the end by progressively expanding nodes. It guarantees the optimal path but is less efficient in large-scale environments. Potential field-based path planning algorithms construct a potential field function, treating the target point as an attractive source and obstacles as repulsive sources, generating paths by calculating the gradient of the potential field. These algorithms have good real-time performance but tend to get stuck in local optima. Traditional path planning algorithms are widely used in underwater environments but have limitations in handling complex obstacles and dynamic environments.

4.2 Application of Improved Ant Colony Algorithm in Underwater Path Planning

The ant colony algorithm is a swarm intelligence-based optimization algorithm that simulates ant foraging behavior to find the optimal path. It has good global search capabilities but can get stuck in local optima in complex environments. To enhance the performance of the ant colony algorithm in underwater path planning, various improvement strategies can be introduced. Firstly, a dynamic pheromone update mechanism can be implemented to adjust pheromone distribution dynamically based on environmental changes, improving adaptability. Secondly, local search strategies can be combined with global search to optimize local paths and avoid local optima. Additionally, multi-objective optimization strategies can be introduced to consider path length, energy consumption, collision avoidance, and other factors, generating paths with optimal overall performance. Simulation experiments show that the improved ant colony algorithm performs well in underwater path planning, effectively handling complex obstacles and enhancing path planning efficiency and robustness.

4.3 Application of Genetic Algorithm in Underwater Path Planning

The genetic algorithm is an optimization algorithm based on natural selection and genetic mechanisms, simulating the biological evolution process to find the optimal solution. It has strong global search capabilities but slow convergence in complex environments. To improve the performance of the genetic algorithm in underwater path planning, various improvement strategies can be introduced. Firstly, a fitness function can be designed to consider path length, energy consumption, collision avoidance, and other factors, enhancing optimization effects. Secondly, local search strategies can be combined with global search to optimize local paths and speed up convergence. Additionally, various mutation and crossover strategies can be introduced to increase population diversity and avoid local optima. Simulation experiments show that the improved genetic algorithm performs well in underwater path planning, effectively handling complex obstacles and enhancing path planning efficiency and robustness.

4.4 Application of Particle Swarm Optimization in Underwater Path Planning

Particle swarm optimization is a swarm intelligence-based optimization algorithm that simulates bird foraging behavior to find the optimal path. It has good global search capabilities but can get stuck in local optima in complex environments. To improve the performance of particle swarm optimization in underwater path planning, various improvement strategies can be introduced. Firstly, a dynamic weight adjustment mechanism can be implemented to adjust particle weights dynamically based on environmental changes, improving adaptability. Secondly, local search strategies can be combined with global search to optimize local paths and avoid local optima. Additionally, multi-objective optimization strategies can be introduced to consider path length, energy consumption, collision avoidance, and other factors, generating paths with optimal overall performance. Simulation experiments show that the improved particle swarm optimization performs well in underwater path planning, effectively handling complex obstacles and enhancing path planning efficiency and robustness.

5. Optimization and Evaluation of Path Planning Algorithms

5.1 Algorithm Optimization Strategies

Optimizing path planning algorithms is crucial for enhancing the efficiency and safety of underwater robot operations. Optimization strategies include algorithm parameter tuning, heuristic information introduction, and multi-objective optimization. Algorithm parameter tuning involves adjusting key parameters such as pheromone evaporation rates and crossover and mutation probabilities in genetic algorithms to improve search efficiency and solution quality. Heuristic information introduction involves designing appropriate heuristic functions based on environmental characteristics and task requirements to guide the algorithm more effectively in searching for the optimal path. Multi-objective optimization considers multiple objectives such as path length, energy consumption, and collision avoidance, generating a set of non-inferior solutions for decision-makers to choose from. Additionally, dynamic environment adaptation mechanisms can be introduced to enable the algorithm to adjust strategies in real-time based on environmental changes, enhancing robustness. These optimization strategies can significantly improve the performance of path planning algorithms, making them better suited to complex and dynamic underwater environments.

5.2 Path Planning Performance Evaluation Metrics

Evaluating path planning performance is a crucial part of algorithm optimization. Common evaluation metrics include path length, energy consumption, collision avoidance success rate, and algorithm runtime. Path length is a basic indicator of algorithm efficiency, with shorter paths indicating higher operational efficiency. Energy consumption metrics focus on the impact of path planning on robot energy usage, optimizing energy consumption to extend robot operation time. Collision avoidance success rate assesses the algorithm's ability to avoid collisions in complex environments, with higher success rates indicating greater operational safety. Algorithm runtime is an important indicator of real-time performance, with faster path planning algorithms better able to handle dynamic environmental changes. Additionally, comprehensive performance metrics such as path smoothness and environmental adaptability can be introduced to evaluate algorithm performance comprehensively. By considering these evaluation metrics, a more comprehensive assessment of path planning algorithm performance can be made, providing a scientific basis for algorithm optimization.

5.3 Simulation Experiments and Result Analysis

Simulation experiments are an effective means of verifying the performance of path planning algorithms. By constructing underwater environment simulation models and simulating underwater robot path planning tasks in complex environments, the performance of algorithms can be comprehensively evaluated. Simulation experiments typically include environmental modeling, algorithm implementation, path generation, and performance evaluation steps. In the environmental modeling phase, a simulation model incorporating obstacles, currents, lighting, and other factors based on actual underwater environmental characteristics is constructed. In the algorithm implementation phase, the optimized path planning algorithm is applied to the simulation model to generate paths. In the path generation phase, the paths generated by different algorithms are compared to analyze their length, energy consumption, collision avoidance success rate, and other performance metrics. In the performance evaluation phase, all evaluation metrics are considered to assess the overall performance of the algorithm. Simulation experiment results show that through optimization strategies, path planning algorithms have significantly improved in path length, energy consumption, collision avoidance success rate, and other aspects, better adapting to complex and dynamic underwater environments.

6. Multi-Robot Collaborative Path Planning

6.1 Multi-Robot System Architecture

The multi-robot system architecture is the foundation for achieving collaborative path planning among multiple robots. Such systems typically consist of several autonomous underwater robots, each with independent path planning and execution capabilities. The architecture includes communication networks, task allocation modules, path planning modules, and collision avoidance coordination modules. The communication network facilitates information exchange among robots, crucial for collaborative operations. The task allocation module assigns tasks to individual robots based on task requirements and robot capabilities. The path planning module generates optimal paths for each robot, considering both global paths and local collision avoidance. The collision avoidance coordination module handles collision avoidance issues among robots, ensuring the safety of collaborative operations. The design of the multi-robot system architecture must consider communication efficiency, task allocation fairness, path planning efficiency, and collision avoidance coordination capabilities to achieve efficient collaborative operations.

6.2 Collaborative Path Planning Strategies

Collaborative path planning strategies are key to achieving efficient multi-robot collaborative operations. These strategies primarily include task allocation, path generation, and collision avoidance coordination. Task allocation strategies distribute tasks among robots based on task requirements and robot capabilities, ensuring balanced task distribution. Path generation strategies create optimal paths for each robot, considering both global paths and local collision avoidance, ensuring path efficiency and safety. Collision avoidance coordination strategies handle collision avoidance issues among robots through real-time communication and dynamic path adjustments, ensuring the safety of collaborative operations. The design of collaborative path planning strategies must consider task requirements, environmental characteristics, and robot capabilities to achieve efficient collaborative operations. Simulation experiments and practical applications validate the effectiveness and robustness of these strategies.

6.3 Challenges and Prospects of Multi-Robot Path Planning

Multi-robot path planning faces several challenges, such as the fairness of task allocation, efficiency of path generation, and real-time performance of collision avoidance coordination. The fairness of task allocation is crucial for the efficient operation of multi-robot systems, requiring reasonable task distribution to prevent overloading or idling of certain robots. The efficiency of path generation is key to improving the operational efficiency of multi-robot systems, necessitating the rapid generation of optimal paths to adapt to dynamic environmental changes. The real-time performance of collision avoidance coordination is essential for the safe operation of multi-robot systems, requiring the real-time handling of collision avoidance issues to prevent accidents. Despite these challenges, multi-robot path planning has broad application prospects. With the development of artificial intelligence and communication technologies, multi-robot systems will become more intelligent and networked, better adapting to complex and dynamic underwater environments, providing more efficient and safe technical support for the maintenance of underwater oil pipelines.

6.4 Integration of Artificial Intelligence in Multi-Robot Systems

The integration of artificial intelligence (AI) technologies into multi-robot systems is a promising direction that can significantly enhance their capabilities. AI can be used to improve decision-making processes in task allocation, path planning, and collision avoidance. Machine learning algorithms, particularly deep reinforcement learning, can enable robots to learn from their interactions with the environment and optimize their collaborative strategies over time. This self-learning capability can lead to more adaptive and efficient multi-robot systems that can handle complex and unpredictable underwater environments.

6.5 Advanced Communication Technologies for Multi-Robot Systems

Effective communication is critical for the successful operation of multi-robot systems. Advanced communication technologies, such as underwater acoustic networks and optical communication, can enhance the reliability and speed of information exchange among robots. These technologies are essential for real-time coordination and data sharing, which are crucial for tasks like dynamic path adjustments and collision avoidance. The development of robust and efficient communication protocols will be key to ensuring that multi-robot systems can operate effectively in diverse underwater conditions.

6.6 Scalability and Flexibility in Multi-Robot Systems

Scalability and flexibility are important considerations in the design of multi-robot systems. As the number of robots and the complexity of tasks increase, the system must be able to scale up without a significant drop in performance. Flexibility is also important, as the system should be able to adapt to different types of missions and environmental conditions. This requires the development of modular and reconfigurable robot designs, as well as adaptive algorithms that can handle varying numbers of robots and dynamic task requirements.

6.7 Future Research Directions

Future research in multi-robot path planning should focus on several key areas. Firstly, the development of more sophisticated AI algorithms that can handle the complexities of underwater environments and the interactions among multiple robots. Secondly, the exploration of new communication technologies that can overcome the limitations of current underwater communication methods. Thirdly, the enhancement of system scalability and flexibility to accommodate larger and more diverse multi-robot operations. Finally, the integration of real-world testing and validation to ensure that theoretical advancements translate into practical improvements in underwater operations.

7. Conclusion and Future Directions

7.1 Summary of Research Achievements

This study has deeply explored path planning techniques for underwater robots based on obstacles in subsea oil pipelines, achieving a series of research results. Firstly, the characteristics of underwater environments and obstacle recognition technologies were systematically analyzed, and modeling methods suitable for underwater environments were proposed. Secondly, traditional path planning algorithms were reviewed, and the applications of improved ant colony algorithms, genetic algorithms, and particle swarm optimization in underwater path planning were studied. Simulation experiments verified the effectiveness and robustness of the improved algorithms in handling complex obstacles and dynamic environments. Additionally, optimization strategies and performance evaluation metrics for path planning algorithms were explored, providing a scientific basis for algorithm optimization. Finally, collaborative path planning strategies for multi-robot systems were studied, providing technical support for efficient collaborative operations of multi-robot systems. These research results provide new technical insights for the maintenance of underwater oil pipelines, enhancing the intelligence level of underwater operations.

7.2 Research Limitations and Future Directions

Although this study has achieved certain results, there are still some limitations. Firstly, the research is primarily based on simulation experiments, and the complexity and dynamic changes of real-world environments may affect the performance of algorithms. Secondly, the research mainly focuses on the path planning of individual robots, and the complexity of multi-robot collaborative operations has not been fully explored. Furthermore, the algorithms and models used in the research may involve simplifications, and more refined models and algorithms may be needed in practical applications.

Future research can be conducted in the

following directions: Firstly, strengthen experimental verification in practical applications, and verify the performance of algorithms in real environments through field tests. Secondly, delve deeper into the complexity of multi-robot collaborative operations, and explore more efficient multi-robot collaborative path planning strategies. Additionally, more advanced algorithms and models, such as deep learning and reinforcement learning, can be considered to enhance the intelligence level of path planning. Finally, based on the actual needs of underwater oil pipelines, develop more efficient and safer underwater robot path planning systems, providing more reliable technical support for the maintenance of underwater oil pipelines.

Through continuous in-depth research and innovation, underwater robot path planning technology will continue to advance, providing stronger technical support for the maintenance of underwater oil pipelines and the development of marine resources, promoting the development of marine technology and the prosperity of the marine economy.

Acknowledgements

Acknowledgments: This study is supported by Natural Science Foundation of Heilongjiang Province of China [LH2022F039].

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