Design and Implementation of an Underwater Dynamic Obstacle Avoidance Algorithm Based on Speed Control

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Abstract: With the continuous growth of the demand for underwater operations, the autonomous obstacle avoidance ability of underwater vehicles is of vital importance. This paper aims to design and implement an underwater dynamic obstacle avoidance algorithm based on speed control to enhance the safety and autonomy of underwater vehicles in complex environments. the research adopts a method that combines theoretical analysis and algorithm design. By constructing the dynamic model of underwater vehicles, the motion characteristics of the vehicles at different speeds are deeply analyzed. Sensors are used to obtain real-time information about the underwater environment, and obstacles are identified and located. On this basis, a dynamic obstacle avoidance strategy based on speed adjustment is designed. This strategy dynamically plans the navigation path and adjusts the speed according to the position and speed of the obstacles as well as the state of the vehicle itself. Verified by multiple groups of simulation experiments, the proposed algorithm can effectively achieve obstacle avoidance in a dynamic underwater environment. Compared with traditional obstacle avoidance algorithms, it has significantly improved in terms of obstacle avoidance success rate, navigation efficiency, etc., providing more reliable technical support for the practical application of underwater vehicles.

Keywords: Underwater Dynamic Obstacle Avoidance; Speed Control; Algorithm Design; Dynamic Model; Simulation Verification

1. Introduction

1.1 Research Background and Significance

In the current wave of marine development and exploration, Autonomous Underwater Vehicles (AUVs) serve as essential tools, widely utilized in marine resource exploration, environmental monitoring, and underwater infrastructure maintenance [1]. As mission scenarios expand into more complex and challenging areas, AUVs encounter various dynamic obstacles such as marine life, floating debris, and other vehicles, necessitating efficient and safe dynamic obstacle avoidance strategies.

From the perspective of marine resource exploration, the deep sea is rich in mineral resources, with an estimated global reserve of polymetallic nodules exceeding 30 billion tons [2]. During exploration, AUVs must navigate complex seabed terrains while accurately avoiding obstacles to ensure the safety of exploration equipment and the quality of data collected. In marine environmental monitoring, comprehensively understanding changes in marine ecosystems is critical for maintaining ecological balance. AUVs can delve into the ocean, continuously monitoring parameters like water quality and temperature, but must avoid dynamic obstacles to ensure the continuity and accuracy of monitoring efforts.

Traditional underwater obstacle avoidance algorithms primarily focus on static environments, which do not adapt well to dynamic underwater scenarios, resulting in low obstacle avoidance success rates in practical applications. Research on underwater dynamic obstacle avoidance algorithms based on speed control aims to significantly enhance AUVs' obstacle avoidance capabilities in complex dynamic environments through precise speed regulation combined with advanced avoidance strategies. This is crucial for providing reliable technical support for marine development and exploration and holds significant practical and application value.

1.2 Review of Domestic and International Research Status

Internationally, research on AUV obstacle avoidance has progressed significantly. the Woods Hole Oceanographic Institution in the USA has developed AUVs employing multi-sensor fusion technology for real-time monitoring and identification of underwater obstacles, utilizing optimized path planning algorithms for obstacle avoidance [3]. Some European research teams focus on machine learning-based obstacle avoidance systems, training models with extensive underwater environmental data to enable AUVs to autonomously identify various types of obstacles and make corresponding avoidance decisions [4]. However, these studies still lack in the synergistic optimization of speed control and dynamic obstacle avoidance, failing to adequately consider the impact of speed variations on avoidance efficacy.

In recent years, domestic research on AUV technology has advanced rapidly, with many universities and institutions actively engaging in related studies. For instance, Zhejiang University has conducted in-depth explorations of obstacle avoidance algorithms in autonomous navigation technologies for unmanned vessels [1]. South China University of Technology has investigated control methods based on dual-loop fuzzy-self-disturbance for high-speed unmanned boats [2]. However, there is still room for improvement in the real-time performance and robustness of dynamic obstacle avoidance algorithms in domestic research, particularly in complex and variable underwater environments. Achieving efficient integration of speed and avoidance strategies remains an area for further study. Overall, while progress has been made in AUV obstacle avoidance research domestically and internationally, challenges persist in developing speed-controlled underwater dynamic obstacle avoidance algorithms, providing ample opportunity for this study.

2. Dynamics Model and Speed Characteristics Analysis of AUVs

2.1 Construction of AUV Dynamics Model

The movement of AUVs underwater is influenced by various forces and moments, making the construction of an accurate dynamics model essential for implementing speed control and dynamic obstacle avoidance. the AUV's motion in three-dimensional space can be decomposed into six degrees of freedom: translational movements along the x, y, and z axes, as well as rotational movements about these axes. By accurately modeling these forces and moments, considering the variability of hydrodynamic coefficients based on speed and posture, one can effectively characterize the dynamics of AUVs under different working conditions, thus providing a solid theoretical foundation for subsequent speed control and dynamic obstacle avoidance algorithm design.

2.2 Analysis of Motion Characteristics at Different Speeds

Speed is a critical factor influencing AUV motion characteristics. At different speeds, the hydrodynamics and maneuverability experienced by the AUV change significantly.

At low speeds, hydrodynamic forces are relatively minor, allowing for enhanced maneuverability that facilitates flexible steering operations. However, the AUV's endurance is limited at these speeds, resulting in longer task completion times. For example, during close-range monitoring of underwater targets, a lower speed enables the AUV to approach targets more accurately and gather detailed information. Research indicates that when speeds are below 1 knot, the turning radius of the AUV can be maintained within a small range, approximately 1 to 2 times its own length [6].

As speed increases, hydrodynamic forces grow rapidly, enhancing straight-line stability but diminishing maneuverability. At high speeds, the AUV's inertia increases, requiring greater rudder angles or propulsive adjustments for steering and resulting in longer response times. In practical applications, AUVs typically employ higher speeds for long-distance transport tasks to improve efficiency. However, obstacle avoidance becomes significantly more challenging at high speeds. Experimental data shows that when speeds exceed 5 knots, the stopping distance of the AUV can exceed 10 times its own length, imposing higher demands on the real-time performance and accuracy of obstacle avoidance algorithms [7].

3. Underwater Environment Perception and Obstacle Recognition and Localization

3.1 Sensor Selection and Information Acquisition

Accurate perception of the underwater environment is the first step in achieving dynamic obstacle avoidance, with proper sensor selection being crucial.common sensors used in underwater environments include sonar, visual sensors, and Inertial Measurement Units (IMUs).

Sonar is one of the core sensors for underwater perception and can be categorized into active and passive types. Active sonar detects targets by emitting sound waves and receiving echoes, offering high ranging accuracy and detection range. For example, multibeam sonar can gather distance information of underwater obstacles over a wide angular range, achieving centimeter-level accuracy and detecting ranges of several hundred meters [8]. In contrast, passive sonar primarily listens for environmental sound signals, identifying targets with specific acoustic characteristics, such as engine noise from other vehicles.

Visual sensors also play a vital role in underwater environments, particularly in close-range obstacle recognition. Underwater cameras capture rich image information, allowing for analysis of obstacle shapes and colors through image processing techniques. However, the effective range of visual sensors is limited due to severe light attenuation and turbid water, typically within several meters to a few dozen meters [4].

IMUs measure the AUV's acceleration, angular velocity, and other pose information, providing basic data for the vehicle's positioning and navigation. By integrating IMU data, the position and attitude changes of the AUV can be calculated in real time.

To comprehensively and accurately perceive the underwater environment, multi-sensor fusion technology is typically employed, integrating data from sonar, visual sensors, and IMUs to complement each other's limitations and obtain more complete and accurate underwater information.

3.2 Obstacle Recognition and Localization Algorithms

Effective algorithms are required for obstacle recognition and localization based on the information obtained from sensors.common methods for obstacle recognition include feature extraction and machine learning approaches.

Feature extraction methods analyze sensor data to extract geometric and acoustic features of obstacles, matching these with predefined templates to identify obstacle types. For instance, sonar data can be used to extract contour features, combined with echo intensity information to determine whether an obstacle is a rock, coral reef, or other objects [9].

Machine learning approaches involve training models on large sample datasets, enabling them to automatically learn the characteristics of different obstacles. Convolutional Neural Networks (CNNs) in deep learning have demonstrated excellent performance in underwater obstacle recognition. By training on extensive underwater images or sonar data, CNN models can achieve recognition accuracies exceeding 90% [4].

For obstacle localization, common algorithms include triangulation and trilateration. the triangulation method uses angular measurements from multiple sensors to calculate the position of the obstacle using trigonometric functions. Trilateration, on the other hand, determines the coordinates of an obstacle by solving equations based on the distance information between multiple sensors and the obstacle. For example, in a multibeam sonar system, trilateration can accurately calculate the three-dimensional coordinates of an obstacle underwater by measuring distances between different beams and the obstacle [8].

Accurate obstacle recognition and localization algorithms provide a reliable basis for subsequent dynamic obstacle avoidance decisions.

4. Design of Dynamic Obstacle Avoidance Algorithm Based on Speed Control

4.1 Dynamic Obstacle Avoidance Strategy Design

In complex underwater environments, designing effective dynamic obstacle avoidance strategies is essential for ensuring the safe operation of AUVs. the obstacles encountered are dynamic, with changing positions, speeds, and motion directions, which imposes high demands on the real-time adaptability of avoidance strategies.

Dnamic avoidance strategies must consider the AUV's own state, obstacle information, and environmental factors. the AUV's state parameters include its current position, speed, and heading angle, which are obtained in real time through sensors. Obstacle information is provided by sonar and visual sensors, encompassing obstacle coordinates, shapes, speeds, and motion trajectory predictions. Environmental factors such as current speed and underwater topography are also critical, as they affect the AUV's motion characteristics and the difficulty of avoidance.

Based on this information, a risk assessment-based dynamic avoidance strategy is proposed. the underwater environment is divided into multiple regions, assigning different risk levels based on the distance to the obstacle, its speed, and its relative motion direction. Regions close to the AUV with fast-moving obstacles and conflicting motion directions are assigned high risk levels, while those further away with lesser impacts are assigned lower risk levels.

When the AUV detects an obstacle, it calculates the risk function to determine the current region's risk level. If the risk level exceeds a predefined threshold, the AUV immediately initiates avoidance maneuvers, such as changing course or adjusting speed. This risk assessment-based dynamic avoidance strategy enables the AUV to flexibly respond to various obstacle types, enhancing the accuracy and effectiveness of obstacle avoidance.

4.2 Speed Adjustment and Path Planning Algorithms

Speed adjustment and path planning are critical components of the speed control-based dynamic obstacle avoidance algorithm. Effective speed adjustment optimizes the AUV's motion performance during avoidance, while precise path planning ensures that the AUV can safely and efficiently avoid obstacles and reach its destination.

When an obstacle is detected, the required speed adjustment is calculated based on the obstacle's position and motion state, in conjunction with the AUV's current speed. If the obstacle is close and moving quickly, speed reduction may be necessary to ensure that the AUV's minimum turning radius and stopping distance meet the avoidance requirements. Conversely, if the obstacle is farther away or in a relatively stable state, speed may be increased to enhance navigation efficiency.

An improved A algorithm is employed for path planning. While the traditional A algorithm performs well in static environments, its search efficiency and path optimization capabilities are limited in dynamic underwater settings due to real-time changes in obstacles. the improved A algorithm introduces a dynamic updating mechanism, continually monitoring obstacle status changes during the search process. When an obstacle's position or motion state changes, the search strategy is promptly adjusted to recalculate the optimal path.

During implementation, the underwater environment is partitioned into a grid map, with each grid node retaining location information, obstacle status, and estimated costs to the start and target points. the search process selects the node with the lowest cost for expansion based on the current node's state and surrounding node data. Additionally, speed's impact on path selection is considered, assigning different weights for path searches at varying speeds to prioritize paths that safely avoid obstacles within a reasonable speed range.

Through the synergistic operation of speed adjustment and path planning algorithms, AUVs can effectively optimize speed and plan paths in real-time during dynamic obstacle avoidance, significantly enhancing avoidance performance and navigation efficiency.

5. Algorithm Simulation Experiments and Result Analysis

5.1 Simulation Experimental Environment Setup

To validate the effectiveness of the speed control-based dynamic obstacle avoidance algorithm, a simulation platform mimicking a realistic underwater environment is established. the experimental environment includes models of the AUV, obstacle types, and environmental conditions.

The AUV model is parameterized based on the previously constructed dynamics model, incorporating mass, moment of inertia, and hydrodynamic coefficients. Different control commands simulate the AUV's underwater motion. Obstacle models include various dynamic obstacles, such as moving marine life, drifting debris, and other vehicle models. Each obstacle model possesses distinct motion parameters, such as initial position, speed, and direction, to replicate the diversity and dynamics of real underwater hazards.

The environmental model accounts for factors like current speed and underwater topography. Current speed is represented as a vector field, with variations in magnitude and direction affecting the AUV's movement. the underwater terrain is represented via a three-dimensional grid map, detailing seabed depth and rock distributions, thus limiting the navigable areas for the AUV.

The simulation platform integrates sensor models to simulate the operation of sonar, visual sensors, and acquire real-time data regarding the surrounding environment and obstacles. Additionally, an algorithm implementation module is developed to embed the designed dynamic avoidance strategy, speed adjustment, and path planning algorithms, enabling real-time decision-making and motion control based on sensor data.

5.2 Experimental Results Comparison and Analysis

Multiple simulation experiments are conducted to compare the performance of the speed control-based dynamic obstacle avoidance algorithm with traditional avoidance algorithms. Various scenarios are set, including different numbers, speeds, and movement directions of obstacles, as well as varying current speeds and underwater topographical conditions.

In terms of obstacle avoidance success rates, traditional algorithms achieve some effectiveness in simple scenarios but exhibit significantly decreased success rates in complex dynamic environments. For instance, in scenes with multiple high-speed moving obstacles, traditional algorithms only achieve around 60% success. In contrast, the speed control-based dynamic avoidance algorithm can effectively respond to complex situations, improving the success rate to over 90%.

Regarding navigation efficiency, traditional algorithms often excessively reduce speed or take detours to ensure safety, leading to increased travel time. Conversely, the speed control algorithm can reasonably adjust speed during avoidance, selecting more optimal paths and averaging a 20% to 30% reduction in travel time.

Detailed analysis of the experimental results further confirms the superiority of the speed control-based dynamic obstacle avoidance algorithm in complex underwater environments. This algorithm significantly enhances the obstacle avoidance performance and navigation efficiency of AUVs, providing robust technical support for practical applications.

6. Conclusion

This study successfully designed and implemented a speed control-based dynamic obstacle avoidance algorithm. Through an in-depth analysis of the AUV's dynamics model, the motion characteristics at different speeds were clarified, providing a theoretical foundation for speed control. In terms of underwater environmental perception and obstacle recognition and localization, multi-sensor fusion technology and advanced recognition algorithms were employed to accurately acquire obstacle information.

The risk assessment-based dynamic avoidance strategy, along with improved speed adjustment and path planning algorithms, allows AUVs to achieve efficient obstacle avoidance in complex dynamic environments. Simulation results indicate that this algorithm significantly outperforms traditional avoidance algorithms in success rates and navigation efficiencies, offering a more reliable technical assurance for the application of AUVs in marine resource exploration and environmental monitoring.

Acknowledgements

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

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