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Intelligent Detection of 3D Anchor Position Based on Monte Carlo Algorithm

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Abstract: With the increase in port throughput and the development of the trend of large-scale ships, selecting applicable anchor positions for ships and ensuring the rational and comprehensive utilization of anchorage areas have become a key issue in utilizing the rate of anchorage resources, ensuring the safety of ships anchoring operations and promoting the development of the shipping industry. Existing anchor position selection and detection algorithm studies are limited to a two-dimensional plane for ship anchor position selection, with few studies considering intelligent detection algorithms for safe ship anchoring water depths based on three-dimensional space, considering conditions such as wind and waves. By considering water depth conditions and the objectives of anchorage safety issues, this study proposes an intelligent detection method for ship anchor detection to find the ship's ideal anchor location in the anchorages by applying the Monte Carlo algorithm. In the processing step, in combination with the Monte Carlo random plane anchor position detection algorithm and Monte Carlo random sampling water depth detection method, the anchor position circle radius model, safe spacing model, anchoring area detection model and safe water depth model are used for examining the anchorage area for awaiting the ship in three-dimensions. To verify the accuracy of the proposed model, based on the scale of common ship types and considering the most conservative parameters, a series of simulation experiments are conducted to check whether the water depth meets the requirements and fully ensure the safety of the experimental results. The research results indicate that the detection almost cover the whole anchorage area and obtain safe water depth restrictions. This method helps to improve the efficiency of ship anchoring and makes actual anchoring operations safer. Under the premise of ensuring sufficient safe spacing between ships, the anchorage ground can accommodate more ships and simulate multi-type ship anchor position detection operations concerning various ship-type parameters to further ensure the safety of ship anchoring.

Keywords: marine operation; anchorage selection; intelligent detection; Monte Carlo algorithm; 3D detection

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1. Introduction

1.1. Background

In recent years, the world shipping market has witnessed rapid development, with an increase in the volume of oil, bulk cargo, and container shipment year by year. This growth is accompanied by noticeable trends toward largescale, deepwater, and intelligent ships. The flourishing maritime industry has led to continuous growth in port throughput, accompanied by improvements in both the speed and quality of port development. Anchorage, as a fundamental requirement and vital infrastructure for maritime development, plays a crucial role in enhancing port efficiency, ensuring that navigational channels remain clear, and promoting safe navigation. With the escalating demand for maritime transportation in commercial trade, the efficient and secure operation of anchorages has become an essential task.

As a major maritime nation, China is actively promoting the development of intelligent ship technology. The China Classification Society (CCS) has outlined the "Specifications for Intelligent Ships", which define intelligent ship technology as the automatic perception and acquisition of data and information about the ship, the maritime environment, logistics and ports through the use of sensors, communication and Internet of Things (IoT). On the basis of computer technology [1], auto-control technology [2], and big data mining and analytics [3,4], intelligent ships are capable of achieving intelligent operations in ship navigation [5], management [6], maintenance [7], and cargo transportation [8]. These advancements aim to enhance ship safety, environmental friendliness, cost-effectiveness, and reliability. Consequently, research on intelligent ship technology plays a crucial role in facilitating the digital transformation and smart development of the maritime industry.

1.2. Literature Review

The study of various resources in the port systems, such as anchorages, waterways, berths, sizes of loading and unloading equipment and transportation equipment, has received considerable attention by researchers. The existing literature related to anchorage is usually based on optimization algorithms or models for anchorage allocation and planning, anchorage capacity design, and so on.

Regarding the allocation of ship anchorages, Malekipirbazari et al. [9] optimized the algorithm and introduced a heuristic algorithm to modify the maximum null priority algorithm to optimize space utilization. The study of Madadi, Bahman et al. [10] further considered the temporal dynamics by taking into account ship arrivals and departures and dynamically placing them in the polygonal anchorage and proposed a spatiotemporal approach to solve this multi-objective anchorage planning problem. Huang et al. [11] focused on the nature of anchorage utilization capacity and argued that the utilization capacity of an anchorage depended on the selection of the actual anchorage position of a ship. Oz et al. [12] built on Huang's work and for the first time, considered a ship's anchorage safety while studying the anchorage allocation problem. Their algorithm significantly improved the safety of anchor position allocation while mainly maintaining a similar level of utilization. In addition, a few researchers have also studied anchorage construction and mooring planning from the perspectives of marine space planning [13] and mooring system [14] as a way to further optimize ship anchorage allocation. In recent years, Cao et al. [15] introduced an innovative intelligent detection algorithm specifically designed for the anchorage areas of maritime autonomous surface ships (MASSs) that are single-moored. They enhanced both the mooring radius model and the safety distance model for moored vessels, significantly advancing the intelligent development of anchorage allocation technology. Zhao et al. [16] proposed a dynamic multi-objective optimization model for anchor position allocation, which not only considered the dynamic change of anchorage occupancy, but also took into account the dual objectives of safety and capacity maximization, and realized the efficient and safe use of anchorage resources by optimizing the arrangement of vessel positions.

In terms of anchorage capacity design, Park et al. [17] calculated the anchorage operation rate of the port through the Anchorage Operation Rate model (AOR model) and evaluated the available anchorage capacity. Kwon et al. [18] proposed the concept of "anchorage capacity index", which provides a more scientific and accurate method for planning the number of terminals in the port, through the refined calculation of the berthing demand of the incoming ships according to the tonnage. This index provides a more scientific and reasonable basis for the planning of the number of port terminals, and solves the problem of only studying the adequacy of designated berths without considering the expansion of berthing capacity. Guo et al. [19] proposed a new multi-objective optimization model of maximum anchorage capacity reliability and minimum anchorage redundancy area from the uncertainty of inbound and outbound ship sizes and arrival times, which solved the problem of the fact that the actual capacity that can accommodate ships is lower than the designed capacity.

Researchers have studied anchorage allocation from different perspectives, and the core objective is to optimize the utilization efficiency of anchorage resources so as to improve the smoothness of ship operations and economic benefits. However, the key to achieve this goal not only lies in the spatial allocation of anchorage, but also involves the design of anchorage capacity. A reasonable design of anchorage capacity can ensure that ships can be safely and stably anchored under various sea conditions, which in turn can support an efficient and orderly anchorage allocation system, forming a virtuous circle and jointly promoting the overall effectiveness of port operation.

1.3. Discussion of Previous Methods

In summary, the existing studies on ship anchorage mainly focuses on two aspects: (1) the problem of anchor position allocation on how to maximize the utilization rate and reduce the risk of ship collision in the limited anchorage space and (2) the problem of how to maximize the capacity of anchorage and improve the operation rate of anchorage. So far, only a few studies have considered the problem of anchorage detection, and there are fewer studies on the anchorage area of ships and intelligent anchor position detection, and even fewer works on anchor position detection in three-dimensional space considering the influence of water depth conditions. In addition, the available studies are unable to address the demands of the development of intelligent ship technology; furthermore, the anchor position selection of ship anchoring needs to be supported by accurate detection methods.

In practical maritime operations, ships must possess the capability to detect suitable anchor positions at the starting and destination ports, as well as along the navigation route, to meet various needs such as emergencies, cargo handling, embarkation and disembarkation of personnel, and anchoring. Currently, traditional methods for selecting ship anchor positions rely on limited factors, such as empirical judgments based on ship distribution, water depth, seabed conditions, and weather conditions, leading to low accuracy and poor real-time performance. Consequently, these methods fail to meet the requirements of modern maritime practices. In practice, to ensure the safety of ship anchoring, larger anchorage radii are often chosen, resulting in the inefficient use of anchorage resources. Conversely, selecting too small anchorage radii poses potential risks. At the same time, the limited availability of deepwater berths in many harbors has resulted in large vessels having to operate offshore at anchor, resulting in congested anchorages, as depicted in Figure 1. During periods of high wind speeds, the risk of dragging anchors due to tidal fluctuations increases, posing safety concerns for anchored vessels and necessitating emergency evasive maneuvers. Moreover, ships may encounter situations requiring anchoring in both shallow and deep waters during their operations, and from a seafarer's perspective, "consideration should be made of the depth of water, the type of stranding site, and the removal of submerged obstructions". A poorer holding ground increases the risk of anchor-dragging [20]. However, existing anchor position detection methods often overlook water depth conditions, leading to a reduced detection accuracy or failure in complex underwater environments, while some existing technologies can provide anchor position detection that accounts for both surface conditions and water depth, leading to practical issues such as low anchoring precision and significant safety hazards during operations. As a result, there is a lack of scientific and universally applicable anchor positioning techniques for different water depth conditions. The rational planning and selection of anchored locations by vessels to maintain safety during anchoring operations represent a significant challenge for ship intelligent detection technologies. This study aims to address these challenges and develop advanced anchor positioning techniques, incorporating judgments of anchorage water depth into consideration alongside ship size and distribution, which will enhance the accuracy of ship anchor position selection, aligning with practical navigation needs and playing a crucial role in maximizing anchorage resource utilization.

Figure 1. The degree of congestion of anchorage ships.

The emergence of 3D ship anchor position intelligent detection methods can effectively provide assistance to vessels in swiftly identifying suitable anchor positions during emergencies, mitigating the impacts and losses caused by upstream vessel drag-offs. It also improves the efficiency and safety of marine operations and plays a vital role in maximizing the use of anchorage resources.

2. Methodology

In this study, in response to the shortcomings of the above studies and the limitations of the existing methods, a new three-dimensional intelligent detection model of anchor position is proposed, which uses the Monte Carlo algorithm to simulate the ship's mooring area, unlike the common two-dimensional planar simulation. In addition, this study increases the safety depth of ship anchoring and constructs a 3D detection model, which provides a more accurate and precise detection method for ship anchoring detection. The method is mainly constructed based on the Monte Carlo stochastic algorithm, the mooring area detection model, etc., which helps to improve the safety and efficiency of ship anchoring, and enable the anchorage to accommodate more ships under the premise of ensuring sufficient safety distance between ships.

2.1. Monte Carlo Stochastic Algorithm

Monte Carlo stochastic algorithm is a computational method based on probabilistic statistics, which is widely used in various engineering fields. The simulation method is realized by a large number of simple repeated sampling, which is less impacted by the limitations of the problem circumstances. It features simplicity and ease of programming, providing relatively accurate solutions. The Monte Carlo stochastic simulation method finds extensive application across various fields, such as the ship lock navigation condition restriction model [21], workspace analysis of robotic arms [22–24], reliability analysis in geotechnical engineering [25], risk analysis in hazardous material transportation [26], risk analysis in transportation systems [27], etc. The problem of ship anchorage area detection shares the same scientific principle as solving these engineering problems, which involves simulating multiple uncertain factors through random sampling under given input conditions to ultimately obtain comprehensive and reliable analytical results. Therefore, by drawing on the successful applications of the Monte Carlo method in other engineering fields, the rationality and feasibility of using this method for ship anchorage area detection can be justified.

In this study, the algorithm simulates various factors within the anchorage area, such as ship positions, by generating random numbers to obtain a range of possible outcomes. By repeating the simulation calculations multiple times, a stable anchor position can be obtained, which serves as a basis for accurately detecting suitable anchor positions in subsequent steps. In addition, the Monte Carlo stochastic algorithm is also used to randomly sample points within the area to calculate the feasibility of the ship anchoring at different positions. Through repeated simulation calculations, the optimal anchor position can be determined, thereby avoiding anchor accidents and vessel damage caused by insufficient or excessive water depths.

2.2. Anchor Position Circle Radius Model and Safe Spacing Model

Different countries and regions have different standards for outgoing chain length, and the outgoing chain length of Chinese moored ships is the largest under different water depths, which is the most conservative and safe, as shown in Table 1. Therefore, this study adopts a simplified model for anchoring radius based on the standard of outgoing chain length of Chinese anchored vessels.

Table 1. Anchor outgoing chain length modeling.

Standards	Conditions	Anchorage Conditions	Length of Outgoing Chain (m)
Chinese Standard (General Vessels) [28]		wind force ≤ 7	$3H + 90$
		wind force > 7	$4H + 145$
Japanese and British Standards [29]	Offshore waiting for vessels or loading and unloading cargo	good anchoring conditions	$6H$
		poor anchoring conditions	$6H + 30$
	Storm anchorage	wind speed 20 m/s	$3H + 90$
		wind speed 30 m/s	$4H + 145$
Dindar Oz			$R = \sqrt{\left(25\sqrt{H}\right)^2}$

The calculation formula is shown in Equation (1):

$$\begin{cases} R = L + 3H + 90, (\text{windforce} \leq 7) \\ R = L + 4H + 145, (\text{windforce} > 7) \end{cases} \quad (1)$$

In addition, in order to ensure the accuracy of the experiment, the model was built on the basis of Equation (1) by taking into account the influence of the hazards of dangerous goods ships such as oil, liquefied gas and chemical ships on the safety distance. To achieve this, the safe distance between two anchored vessels should satisfy Equations (2) and (3):

$$\begin{cases} D_S \geq \sigma R_1 + \tau R_2 \\ R_1 = L_1 + 3H + 90 \quad (\text{wind force} \leq 7) \\ R_2 = L_2 + 3H + 90 \end{cases} \quad (2)$$

$$\begin{cases} D_S \geq \sigma R_1 + \tau R_2 \\ R_1 = L_1 + 4H + 145 \quad (\text{wind force} > 7) \\ R_2 = L_2 + 4H + 145 \end{cases} \quad (3)$$

where D_s represents the safe distance between ships; L_1 and L_2 represent the length of the existing anchored ship and the ship to be anchored, respectively; H stands for water depth;

R_1 and R_2 are the radii of the anchor circle, which pertain to both the current anchored vessel and the vessel planned for anchoring; σ and τ represent the lower and upper limits of ship type coefficient, respectively, where $\sigma, \tau \in [1, 1.2]$; when the ship is an ordinary cargo ship, take the lower limit, and when the ship is an oil product, liquefied gas and chemical ship, take the upper limit [30].

2.3. Anchoring Area Detection Model

By creating the Plane Rectangular Coordinate System for the anchorage area, two-dimensional coordinates are assigned to existing vessels in the anchorage or other obstacles that hinder anchoring operations. By using the Euclidean metric method to develop a model for detecting the anchoring position of vessels. This model helps in selecting an anchoring position that maintains a safe distance between ships, as shown in Equation (4):

$$\begin{cases} d_n = \sqrt{(x_a - x_n)^2 + (y_a - y_n)^2} \\ Min(d_n) \geq D_s \end{cases} \tag{4}$$

where (x_n, y_n) represents the location of existing ships or other obstacles hindering anchoring operations in the Cartesian coordinate system where the anchorage is located. (x_a, y_a) denotes the anchoring location that conforms to the safe distance between anchored ships.

2.4. Safe Water Depth Model

In this study, the ship's requirement for the rich water depth for anchoring in the anchorage is used, which is calculated as Equation (5):

$$\begin{cases} h = k \times d + h_w \\ h > H_m \end{cases} \tag{5}$$

where h indicates the required anchoring safety water depth for the ship to be anchored; d denotes the maximum draft of the ship during anchoring; k is the sheltering coefficient, which takes 1.2 when there is no surge or good sheltering and 1.5 when there is a surge or bad sheltering [31]; h_w signifies the wave surplus depth, typically ranging from 2 to 3 m; and H_m denotes the simulated draft depth of the ship to be anchored. In order to increase the safety of anchor position selection, the sheltering coefficient k is taken as the upper limit value, which can help to take into full consideration the safety hazards caused by poor sheltering, longitudinal swaying of the ship, surge and other adverse conditions in the subsequent simulation test [31]. The wave-rich water depth is taken as 20% of the ship's maximum draft according to the recommendation of the British "Offshore Buildings" in the initial stage.

3. Simulation Experiment

3.1. Procedure

To verify the validity of the Monte Carlo anchor area detection model, simulation experiments are conducted following the specific steps outlined below, and Figure 2 shows the model-solving logic.

Step 1: Construct a three-dimensional anchorage area of size 3n nautical miles by 3n nautical miles using MATLAB simulation software (version R2021a), where the water depth ranges from 20 to 40 m.

Step 2: Obtain obstacle information within the anchorage area and the two-dimensional coordinates of existing ships using information acquisition equipment such as Automatic Identification System (AIS) or radar equipment; denote the coordinates as (x_1, y_1), (x_2, y_2)......(x_n, y_n), mark the set of coordinates as S_b, and import this information into an improved ship anchoring radius model to calculate the anchoring radius of existing ships.

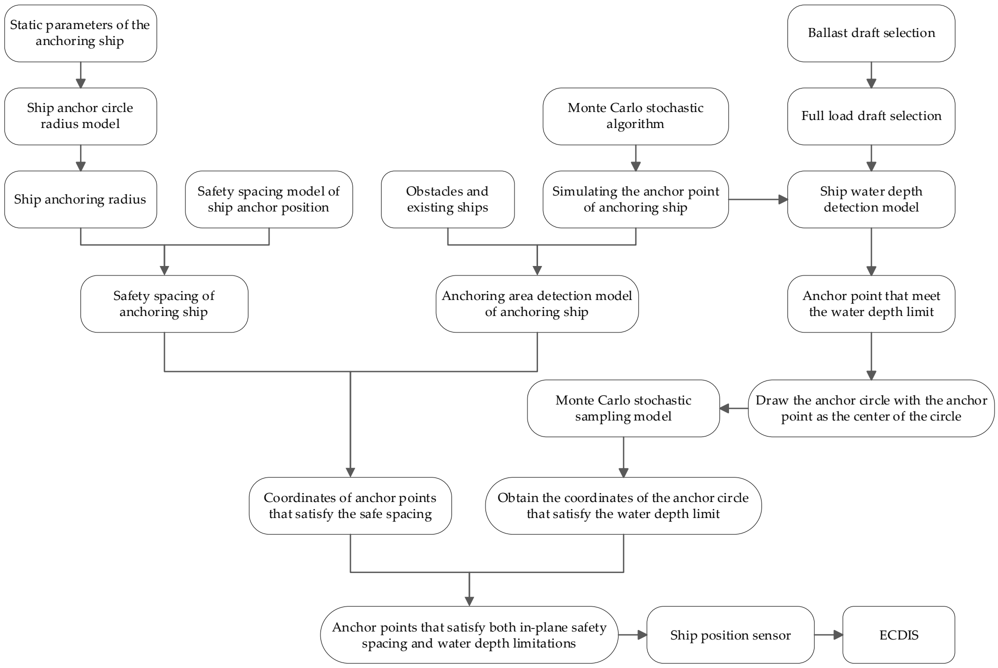


Figure 2. Model-solving logic.

Step 3: Using the two-dimensional coordinates of the anchorage obstacle from step 2 as the center of the circle, set a safe radius R_d of the restricted water area with a set of coordinates S_d.

Step 4: Input relevant information such as ship length and anchor chain length of existing ships into the safety spacing model as shown in Equation (2) or Equation (3) to calculate the anchoring radius and ship safety spacing value D of existing ships.

Step 5: Use the Monte Carlo random plane anchor position detection algorithm to generate n sets of two-dimensional coordinates, which represent the choice of anchor points for ships awaiting anchor by the simulated ship to be moored, and the set of these coordinates is denoted as S_m. The essence of the algorithm is to perform anchor position detection in the plane by random sampling in the horizontal plane to simulate the vessel position according to the characteristics of the Monte Carlo stochastic algorithm.

Step 6: Utilize the anchoring area detection model shown in Equation (4), the coordinate sets S_b and S_m are iteratively calculated to obtain the two-dimensional coordinates (X_{e1}, Y_{e1}), (X_{e2}, Y_{e2})......(X_{ei}, Y_{ei})......(X_{en}, Y_{en}) of the anchoring points of the ship to be anchored that satisfy the value D of the ship's safety spacing in Step 4, and the coordinate set of which is S_e.

Step 7: Using S_e as the center and the anchoring radius as the radius, draw an anchor position circle. Within the anchor location circle, the anchor location circle was sampled using a Monte Carlo random sampling water depth detection. The principle of this method is to use the random function to set the angle and radius of the simulated sampling point, and subsequently use the polar coordinate formula to calculate the coordinates of the extracted point in the plane right-angled coordinate system to complete the random sampling of the anchor position circle, and then detect the water depth. After the first random sampling, add the water depth verification results of the sampled points as an additional data dimension, indicating whether the water depth meets the requirements. $(x_r, y_r, h_r, 1)$ stands for where the safety water depth limit is met, while $(x_r, y_r, h_r, 0)$ represents points where it is not met. (x_r, y_r, h_r) represents the sampling point, and the data of the water depth verification operation is incorporated into the collection S_{S1}. When the second random sampling is conducted, the sampling point is compared with the data points in the collection S_{S1}, and if there is such a data point, then the water depth verification data are taken directly. For the points with no data in S_{S1}, then the data values are incorporated into the collection S_{S2} after water depth verification. Compare the collection S_{S2} with the draft depth values of vessels awaiting anchor to obtain anchoring points for vessels that satisfy both two-dimensional and three-dimensional depth requirements. The point collection is recorded as S_f, and judgment S_f within the coordinates of the point as the center of the circle within the anchoring circle is not within the point collection S_d. When the requirements of the point collection are met, this is recorded as S_g, and the following are subsequently marked: $(\varphi_1, \lambda_1, h_1)$, $(\varphi_2, \lambda_2, h_2)$......$(\varphi_i, \lambda_i, h_i)$......$(\varphi_m, \lambda_m, h_m)$. The data set relationship is shown in Figure 3.

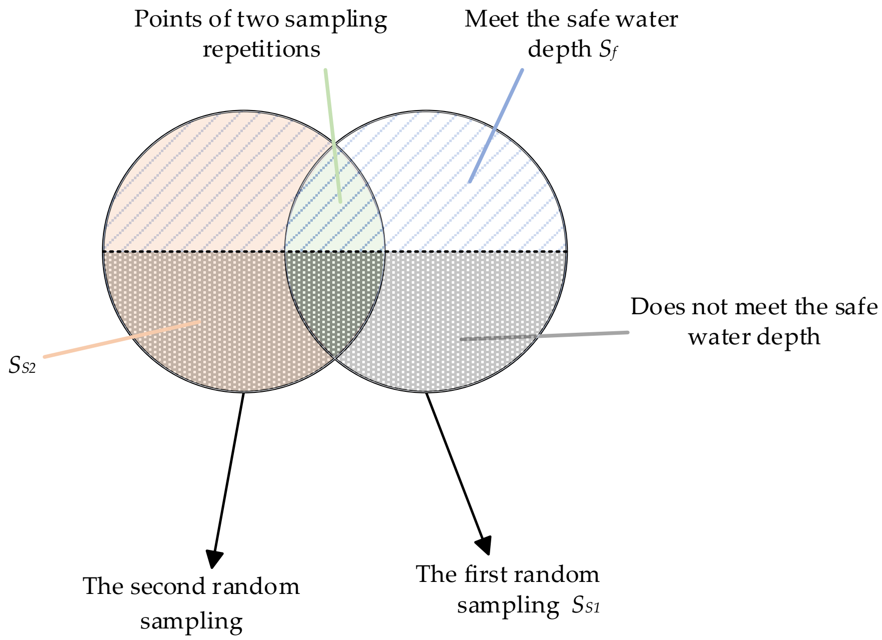


Figure 3. Data set relation.

Step 8: Convert the three-dimensional anchoring point coordinates obtained in Step 7, which satisfy safety spacing and water depth restrictions, into anchoring points understood by ship position sensors, and transmit these coordinates to electronic charts or other relevant devices for ships awaiting anchor to select suitable positions for anchoring operations as practically needed.

3.2. Parameter Setting

In order to evaluate and compare the influence of different types of ships on anchor position selection, this study constructs an anchoring simulation system. In this system, using real data from the ship's design-type scale and synthetic data obtained through Monte Carlo simulation, a three-dimensional intelligent anchor position detection algorithm combining the Monte Carlo random plane anchor position detection algorithm with Monte Carlo random sampling depth detection is experimentally applied to determine the anchor position selection for the ship to be anchored.

In this experiment, a three-dimensional anchorage sea area of 3 nautical miles $*$ 3 nautical miles is defined by MATLAB program. The depth of the anchorage is determined with reference to the anchorage depth data of Ningbo Zhoushan Port, which is one of the top three of the top ten ports in the world. Ningbo Zhoushan Port is known for its rich anchorage resources, with a wide range of depths, from shallow to deep, ranging from 3 to 51 m. Considering the anchoring needs and safety of large commercial vessels, a water depth between 20 m and 40 m is particularly suitable, which can ensure the stable anchoring of the vessels and avoid the inconvenience of operating in too deep water. Therefore, this study carefully constructs a three-dimensional simulation of the mooring area, focusing on the 20-to-40-m water depth section, based on the detailed anchorage depth data of Ningbo Zhoushan Port, to accurately match and meet the actual needs of most commercial vessels.

The ship types selected for the experiments of this thesis are closely based on the common ship types in the inter-provincial coastal freight ship capacity analysis report authoritatively released by the government. Meanwhile, in the current shipping market, bulk carriers and container ships have the largest transportation volume and a high demand for ships. By referring to the relevant data from government websites and the current market trends, we are able to ensure that the ship types selected in the experiment match the current development trends and actual needs of the shipping industry, which ensures the academic rigor of this study. Specifically, we chose chemical tankers, oil tankers, bulk carriers and container ships, and the specific ship type scales are shown in Table 2.

Table 2. Parameters of the selected ship type for simulation experiments.

Ship Name	Ship Type	The Length of Ship (meter)	Masking Coefficient
Ship No. 1	Chemical tanker	127	2.5
Ship No. 2	Oil tanker	185	2.5
Ship No. 3	Bulk carrier	228	2.5
Ship No. 4	Container ship	300	2.5

The anchoring area detection is simulated using MATLAB based on the ship data in Table 2 and the anchor position circle radius model and safe spacing model. Both existing ships in the anchorage and ships waiting to anchor belong to the four types mentioned above. The spacing between the existing ships in the anchorage adheres to the required safety distance standards for anchoring. In addition, under the two wind conditions of wind force ≤ 7 and wind force > 7, combined with the two water depth models of 20 m and 40 m, four types of ship safety spacings can be calculated. Tables 3 and 4 present two groups of anchoring detection data with wind force ≤ 7, while Tables 5 and 6 present two groups of anchoring detection data with wind force > 7.

Table 3. Data of ships maintaining a safe distance from each other with wind ≤ 7 (water depth 20 m) (unit: meter).

No.	The Length of Ship No. 1	The Length of Outgoing Chain	Safety Radius	The Length of Ship No. 2	The Length of Outgoing Chain	Safety Radius	Safety Distance
1	127	150	277	127	150	277	664.8
2	127	150	277	185	150	335	734.4
3	127	150	277	228	150	378	710.4
4	127	150	277	300	150	450	782.4
5	185	150	335	185	150	335	804
6	185	150	335	228	150	378	780
7	185	150	335	300	150	450	852
8	228	150	228	228	150	378	756
9	228	150	300	300	150	450	828
10	300	150	300	300	150	450	900

According to maritime experience, when a ship is sailing in ballast condition, the minimum average draft should be at least 50% of the full load draft; during winter navigation, due to larger waves and winds, it should be between 55% and 60%. These reference data are summarized from the practical experience of ship drivers and are also provided as guidance parameters in the nautical literature [32]. Therefore, in this study, 50% of the full load draft is taken as the calculated value for the draft in ballast condition. In accordance with the data in Table 2 as well as the safety depth model, the demand for safe water depth during ship anchoring is calculated, as shown in Table 7.

Table 4. Data of ships maintaining a safe distance from each other with wind ≤ 7 (water depth 40 m) (unit: meter).

No.	The Length of Ship No. 1	The Length of Outgoing Chain	Safety Radius	The Length of Ship No. 2	The Length of Outgoing Chain	Safety Radius	Safety Distance
1	127	210	337	127	210	337	808.8
2	127	210	337	185	210	395	878.4
3	127	210	337	228	210	438	842.4
4	127	210	337	300	210	510	914.4
5	185	210	395	185	210	395	948
6	185	210	395	228	210	438	912
7	185	210	395	300	210	510	984
8	228	210	438	228	210	438	876
9	228	210	438	300	210	510	948
10	300	210	510	300	210	510	1020

Table 5. Data of ships maintaining a safe distance from each other with wind > 7 (water depth 20 m) (unit: meter).

No.	The Length of Ship No. 1	The Length of Outgoing Chain	Safety Radius	The Length of Ship No. 2	The Length of Outgoing Chain	Safety Radius	Safety Distance
1	127	225	352	127	225	352	844.8
2	127	225	352	185	225	410	914.4
3	127	225	352	228	225	453	875.4
4	127	225	352	300	225	525	947.4
5	185	225	410	185	225	410	984
6	185	225	410	228	225	453	945
7	185	225	410	300	225	525	1017
8	228	225	453	228	225	453	906
9	228	225	453	300	225	525	978
10	300	225	525	300	225	525	1050

Table 6. Data of ships maintaining a safe distance from each other with wind > 7 (water depth 40 m) (unit: meter).

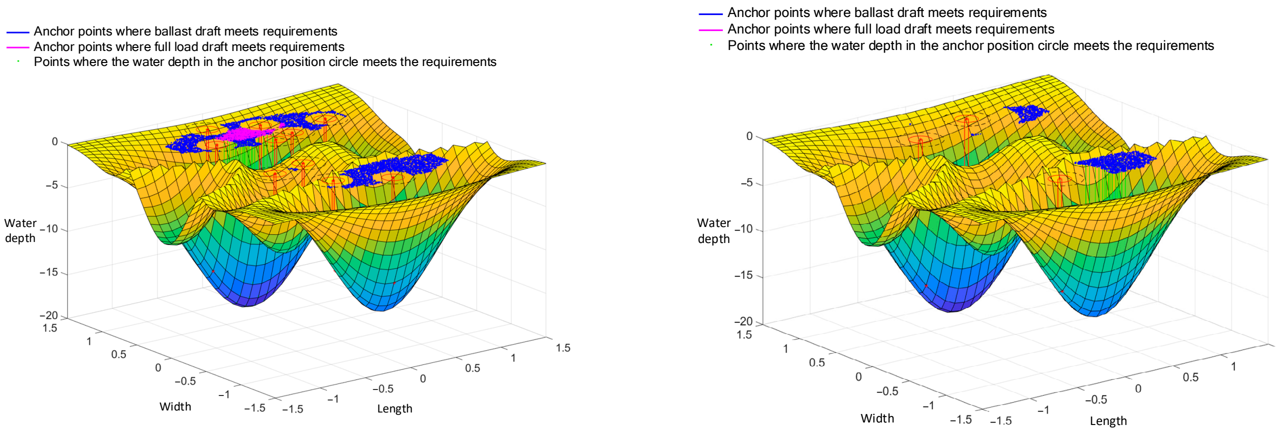
No.	The Length of Ship No. 1	The Length of Outgoing Chain	Safety Radius	The Length of Ship No. 2	The Length of Outgoing Chain	Safety Radius	Safety Distance
1	127	305	432	127	305	432	1036.8
2	127	305	432	185	305	490	1106.4
3	127	305	432	228	305	533	1051.4
4	127	305	432	300	305	605	1123.4
5	185	305	490	185	305	490	1176
6	185	305	490	228	305	533	1121
7	185	305	490	300	305	605	1193
8	228	305	533	228	305	533	1066
9	228	305	533	300	305	605	1138
10	300	305	605	300	305	605	1210

Table 7. Safety water depth data of ship anchoring (unit: meter).

No.	The Length of Ship No. 1	Full Load Draft	Ballast Draft	The Actual Full Load Water Depth	The Actual Ballast Water Depth
1	127	8.4	4.2	12.58	7.54
2	185	12	6	16.9	9.7
3	228	14.2	7.1	19.54	11.02
4	300	14	7	19.3	10.9

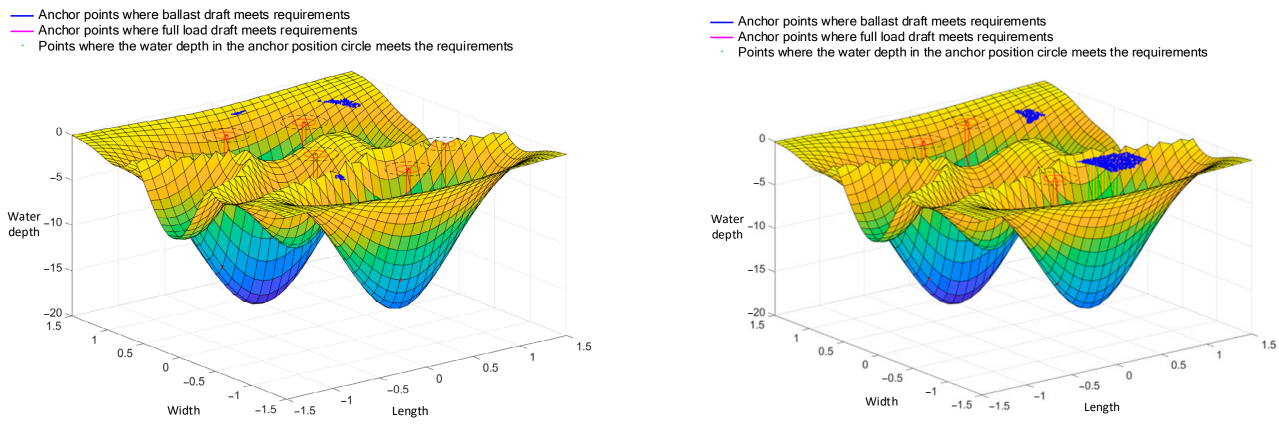
3.3. Results

The above-mentioned data are imported into the MATLAB simulation platform, and the simulation experiments are carried out according to the above steps. The Monte Carlo random simulation algorithm is utilized for simulation and arithmetic operation to detect the ship anchoring areas that meet the requirements for safe spacing and safe water depth. The PLOT function is used to project the areas satisfying the conditions for ship anchoring onto the seafloor in green shading and rendered into three-dimensional graphics. Additionally, 40 three-dimensional images of anchor position detection can be calculated from four sets of data in this experiment. Figures 4–7 randomly provide eight anchor position detection images randomly extracted. Among them, the red dots in the figure simulate the existing ships, while the blue dots represent the drop anchor points that meet the two-dimensional conditions and satisfy the water depth restriction in the unloaded state. The pink dots represent the drop anchor points that further satisfy the water depth restriction in the full load state on the basis of the blue dots. The green dots indicate the drop anchor points that satisfy the conditions for both being generated within the anchoring circle and meeting the water depth requirements, based on the pink dots.



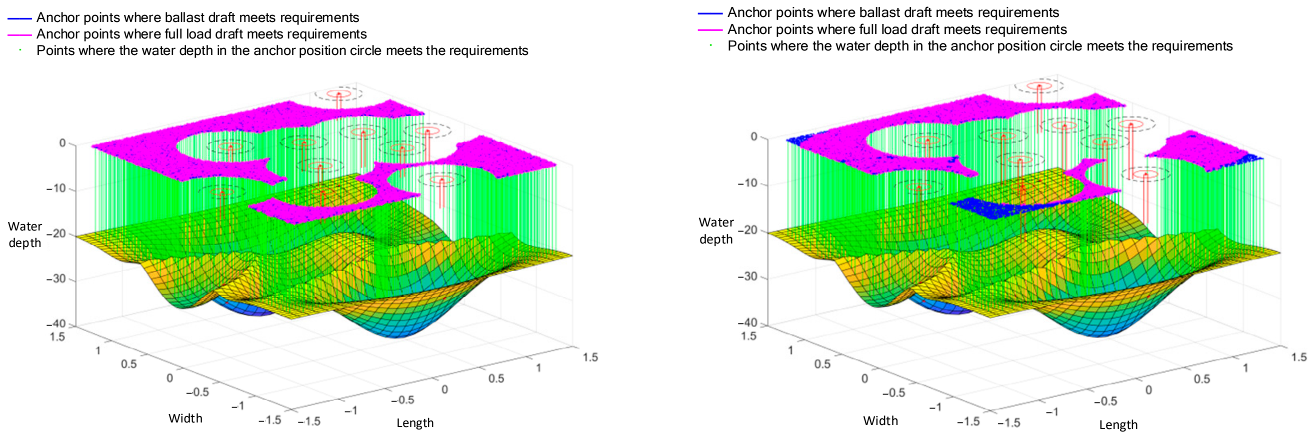
(**a**) (**b**)

Figure 4. Anchoring position detection in a water depth of 20 and wind force ≤ 7: (**a**) 127 m and 185 m ship-type anchoring position detection; (**b**) 228 m and 300 m ship-type anchoring position detection.



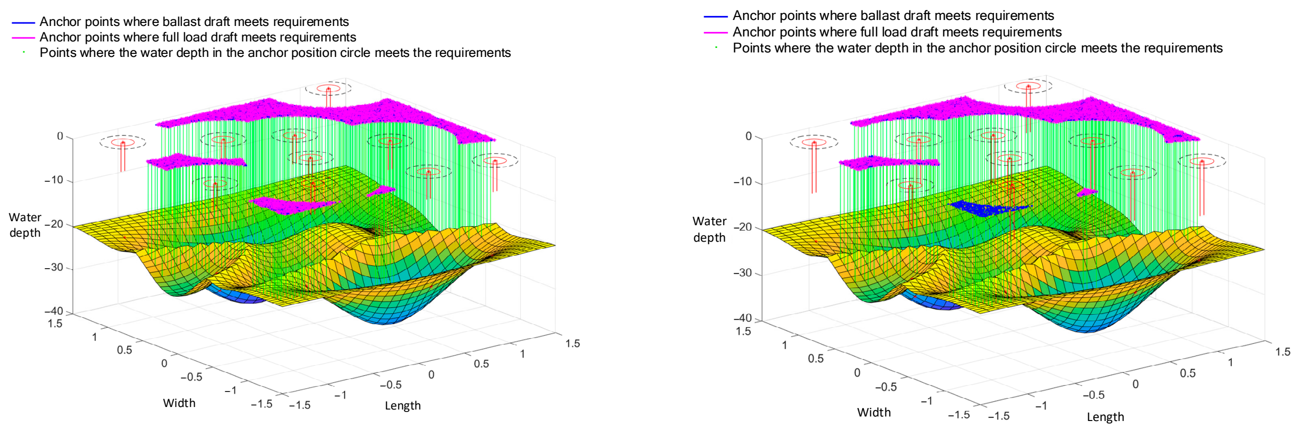
(**a**) (**b**)

Figure 5. Anchoring position detection in a water depth of 20 and wind force >7: (**a**) 127 m and 185 m ship-type anchoring position detection; (**b**) 228 m and 300 m ship-type anchoring position detection.



(**a**) (**b**)

Figure 6. Anchoring area detection in a water depth of 40 and wind force ≤ 7: (**a**) 127 m and 185 m ship-type anchoring position detection; (**b**) 228 m and 300 m ship-type anchoring position detection.



(**a**) (**b**)

Figure 7. Anchoring area detection in a water depth of 40 and wind force > 7: (**a**) 127 m and 185 m ship-type anchoring position detection; (**b**) 228 m and 300 m ship-type anchoring position detection.

Figures 4 and 5 are the 3D detection images of different ship types in the case of a water depth of 20 m and wind force less than 7 and wind force more than 7, where a and b are the different sizes of the ship types. And between Figures 4 and 5 are the different wind speeds, from which it can be seen that the larger the ship type, the fewer the points that meet the requirements, and similarly the larger the wind speed, the higher the requirements for the safety distance, and therefore the fewer the points that meet the requirements.

Figures 6 and 7 are different from Figures 4 and 5 in that the ambient water depth is changed from 20 m to 40 m, and again, the larger the ship size and the higher the wind speed, the fewer the number of points that meet the requirements. However, compared to Figures 4 and 5, a large number of green points can be clearly seen in Figures 6 and 7, which indicates that there are a large number of drop anchor points that satisfy both the safety distance between planar anchor circles and the water depth requirements. This indicates that the ambient water depth becomes deeper and the number of points meeting the requirements increases.

Based on this experiment, it is possible to find out the effect of different boat sizes and load conditions on the anchoring position. The general conclusion is that the larger the boat size and the higher the wind speed, the higher the need for safe distance and water depth.

4. Discussion

In this study, the results of anchor position detection in water depths of 20 m and 40 m in the case of wind < 7 and wind > 7 are investigated. Based on the above experimental results and analysis, we can examine the application effect and potential value of the Monte Carlo stochastic algorithm in 3D intelligent anchor position detection from multiple dimensions and draw the following main conclusions:

1. The 3D intelligent anchor position detection algorithm based on the Monte Carlo stochastic algorithm is randomly sampled 5000 times in MATLAB simulation platform. The calculation results show that the detection area of the algorithm basically covers the whole anchorage area, which ensures the generality of the anchor position detection of this algorithm, and provides an effective reference for studying the waste of anchor position area and the utilization rate of the anchorage area.
2. The intelligent detection method of ship 3D anchor position based on Monte Carlo algorithm takes into full consideration the influence of ship type, wind force and other factors on the safe spacing of ships, and provides a reasonable anchor position selection scheme for ships anchoring in the anchorage area.
3. In order to reflect the accuracy and efficiency of the algorithm, this experiment compares the demand for water depth when the ship is unloaded and fully loaded, so as to intuitively obtain the influence of different water depth parameters of different ship types on the selection of anchoring area.
4. Based on the Monte Carlo stochastic algorithm, the 3D intelligent anchor position detection algorithm can also flexibly change the water depth parameters of the ship's anchoring according to the actual needs, in order to meet the requirements of the ship for the safety of water depth in the selection of the actual anchor position.
5. In order to improve the calculation efficiency, this experiment combines the data set optimization algorithm in the random sampling process. The random sampling time is reduced from the original 38.5 s to 6.5 s, which optimizes a large number of repetitive operations in the 3D anchor position detection algorithm and thus reduces a large number of operations in the water depth detection part, significantly improves the efficiency of the 3D anchor position detection algorithm, and helps to assist the ship to stop the anchor in a timely and rapid manner.

These findings reveal the intrinsic connection between the choice of anchor position and ship type and environmental conditions. This not only deepens our understanding of the complexity of anchor position selection, but also lays a solid foundation for subsequent research and practical applications. Therefore, intelligent 3D anchor position detection based on the Monte Carlo algorithm meets the current needs of nautical practice for anchor position selection for large ships and provides an important theoretical reference for the future research of anchor area planning.

In addition, the algorithm realizes the intelligent planning and optimization of anchor position by simulating a large number of random samples and combining multiple factors such as ship type, wind, water depth, etc. The algorithm provides practitioners with a more reliable, simpler, and more practical method of intelligent anchor detection, which can effectively reduce safety accidents due to an improper selection of mooring depths caused by judgment based on personal experience.

5. Conclusions

The anchor position detection problem is a challenging issue in determining the optimal anchoring position for incoming ships. Previous studies have only considered the utilization and safety aspects of anchorage planning, while overlooking the rationality of ship anchoring positions.

This study aims to fulfill this need by conducting research on an intelligent anchor position detection algorithm in 3D space, based on the 2D anchor position detection method for ships. Through the three-dimensional anchor position intelligent detection algorithm combining Monte Carlo random plane anchor position detection algorithm and Monte

Carlo random sampling water depth detection, the ship's anchoring position suitable for safe water depth under a 3D view is obtained on the basis of repeated simulations, and numerical simulation experiments are carried out to simulate the actual ship entering the harbor and anchoring situations based on the parameters of different ship types. The results demonstrate that this detection algorithm possesses both rapidity and accuracy, resolving the issues of low precision in 2D-plane anchor position detection and reliance on empirical anchoring. It holds practical significance for improving efficiency and safety in the selection of anchor position selection for large-scale and deepwater ships. In practical applications, an intelligent detection algorithm for anchoring area detection is provided, which can be deployed onto ship equipment and display the detected anchoring areas on systems such as Electronic Chart Display and Information System (ECDIS), thereby providing technical support for the anchoring ship to choose safe and controllable anchoring positions.

This study also has the following shortcomings: First, the arbitrary anchor points are not sampled at equal distance intervals; the anchor points with abnormal ship parameters and anchor water depths have not yet been encrypted for sampling to be eliminated; and the accuracy of anchoring operations has yet to be improved. Second, the matching of suitable anchor positions according to the duration of anchoring needs to be further deepened. In order to quickly eliminate anchor points with abnormal anchorage data and improve the accuracy of the algorithm, in the next step, we will combine the algorithm with the moored ship data and increase the sampling density of key anchorage areas on the basis of increasing the training set and validation set. In addition, in order to improve the efficiency of ship operations in the anchorage area, in-depth research on the matching of anchoring time and anchor position is conducted to realize the precise allocation and efficient utilization of anchoring resources.

6. Patents

The patent for this thesis is currently in the application process and has been published.

Author Contributions: Conceptualization, Z.C. and X.Z.; methodology, X.Z. and Z.Z.; software, Z.C.; validation, Z.C. and X.Z.; formal analysis, Z.L. and Y.C.; investigation, M.Z. and X.L.; resources, Y.C. and J.L.; data curation, Z.C. and L.C.; writing—original draft preparation, Z.C.; writing—review and editing, L.C. and Z.Z.; visualization, X.Z. and Z.Z.; supervision, L.C. and Z.Z.; project administration, L.C. and Z.Z.; funding acquisition, L.C. All authors have read and agreed to the published version of the manuscript.

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