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Research on the Problem of Autonomous Collision Avoidance and Risk Avoidance of Ships

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Abstract: This paper deeply explores the autonomous collision avoidance algorithm for intelligent ships, aiming to enhance the intelligence level and safety of ship collision avoidance by integrating navigation experience. An autonomous collision avoidance algorithm based on navigation experience is designed, a collision avoidance experience database is constructed, a quantitative model is established, and specific algorithm steps are implemented. The algorithm is verified and analyzed through simulation tests. The results show that the algorithm can effectively achieve autonomous ship collision avoidance in different scenarios, providing new ideas and methods for the development of intelligent ship collision avoidance technology.

Keywords: Intelligent ships; Autonomous collision avoidance algorithm; Navigation experience; Quantitative model; Simulation test

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1. Introduction

With the development of the shipping industry, the number of ships has been continuously increasing, and the maritime traffic environment has become increasingly complex. Ship collision accidents occur from time to time, posing a serious threat to the safety of life and property at sea and the marine environment. Traditional ship collision avoidance mainly relies on the experience and operation of the ship's crew. In complex environments, it is easy to make judgment errors and fail to operate promptly. The rise of intelligent ship technology has provided a new way to solve the problem of ship collision avoidance [1]. As one of the core technologies of intelligent ships, the autonomous collision avoidance algorithm enables ships to automatically sense the surrounding environment, judge collision risks, and take effective avoidance measures without human intervention. At present, although there have been many studies on ship autonomous collision avoidance algorithms, research on deeply integrating navigation experience into algorithm design still needs to be strengthened. This research aims to utilize navigation experience to design an efficient and reliable autonomous collision avoidance algorithm for intelligent ships, improving the safety and autonomy of ships in complex navigation environments.

2. Design principles of the autonomous collision avoidance algorithm

2.1. Algorithm design concept

The core concept of this algorithm design is to simulate the collision avoidance decision-making process of human drivers during navigation. Firstly, the ship uses various sensors to perceive the surrounding environment information in real-time. This includes dynamic information such as the position, speed, and course of the target ship, as well as static information such as its position, speed, course, and ship dimensions. Subsequently, the perceived information is processed and analyzed [2]. By using the target encounter feature recognition algorithm and the encounter situation recognition algorithm, the current encounter situation is determined, such as a head-on encounter, crossing situation, or overtaking situation. Then, based on the collision risk assessment algorithm, the degree of collision risk between the own ship and the target ship is calculated. According to the encounter situation and the collision risk degree, combined with the rules and cases in the collision avoidance experience database, a decision-making and response algorithm is adopted to generate a reasonable avoidance decision. The avoidance decision includes setting the avoidance parameters of the course autopilot, such as the initial rudder angle and the course adjustment amount. During the avoidance process, the ship's motion state and the changes in the surrounding environment are continuously monitored to determine the re-navigation opportunity. When the re-navigation opportunity arrives, the re-navigation operation is executed to restore the ship to its normal navigation state.

2.2. Algorithm design process

The algorithm process mainly includes stages such as initialization, perception, cognition, decision-making, making and response, execution, and re-navigation (**Figure 1**). In the initialization stage, the parameters required by the algorithm are set, including the ship's initial position, speed, course, etc., as well as the interface parameters of the course autopilot.

In the perception stage, the ship uses sensors (such as radar, AIS, etc.) to obtain real-time dynamic and static data of the ship by integrating the surrounding environment and multi-source information. These data serve as the basis for subsequent algorithm processing.

In the cognition stage, the target encounter feature recognition algorithm and the encounter situation recognition algorithm are used to analyze the perceived data, identify the encounter features of the target ship, judge the encounter situation and the responsibility of the own ship, and determine the current navigation situation.

In the decision-making and response stage, the collision risk level is calculated through the collision risk assessment algorithm. Based on the assessment results and the collision avoidance experience database, a PIDVCA (Proportional-Integral-Derivative Variable Course and Speed Adjustment) scheme is generated and optimized to determine the avoidance decision.

In the execution stage, according to the decision-making results, the avoidance parameters of the course autopilot are set, the avoidance operation is carried out, and it is judged whether the execution time has arrived.

In the re-navigation stage, continuous monitoring is carried out during the avoidance process. When it is judged that the re-navigation opportunity has arrived, according to the preset re-navigation strategy, the course, initial rudder angle, and interface parameters are set, and the re-navigation operation is executed to restore the ship to normal navigation. The entire process forms a closed loop, which is continuously adjusted and optimized based on real-time information to ensure the safe collision avoidance of the ship [3].

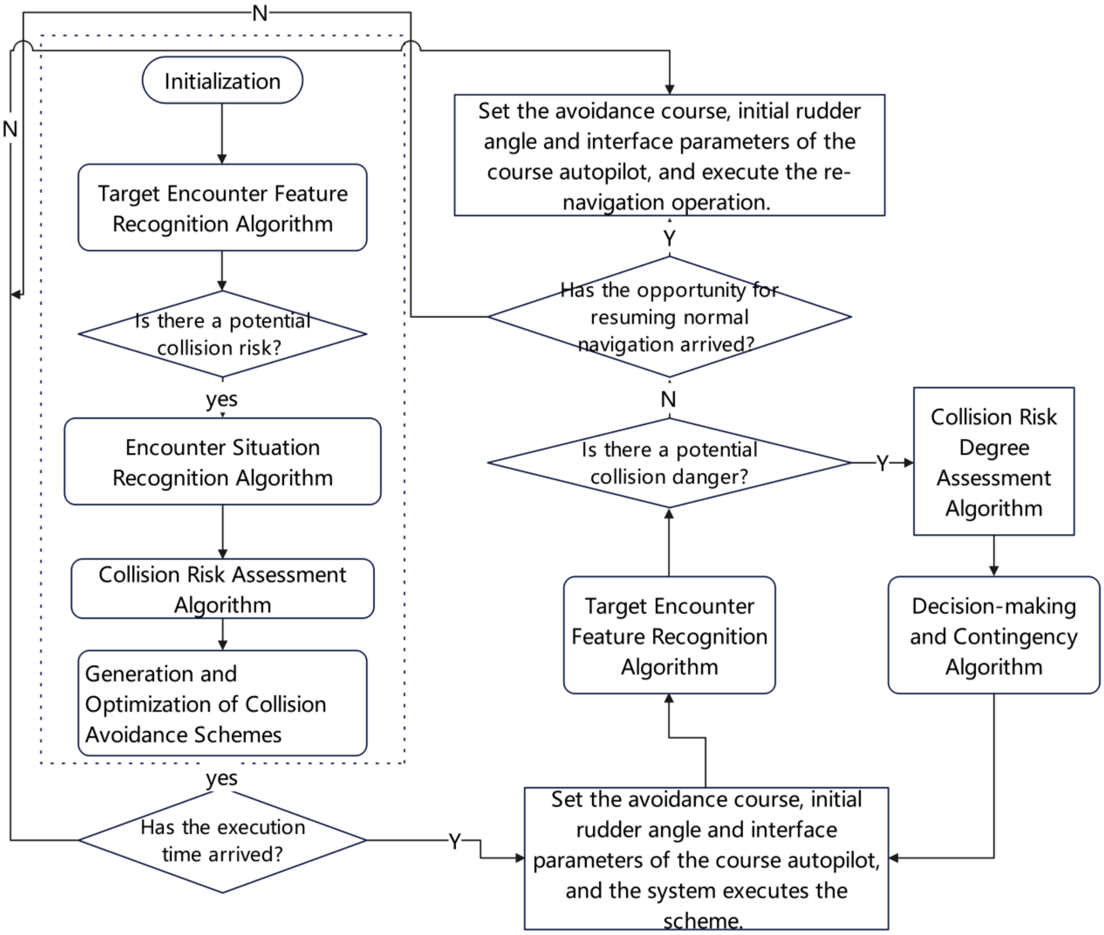

Figure 1. Flowchart of the algorithm design

3. Quantitative design of the autonomous collision avoidance algorithm

3.1. Construction of the collision avoidance experience database

The collision avoidance experience database is composed of a database, a rule base, and a model base. These three components cooperate to form an algorithm library. The database stores the on-site environment and the ship's dynamic and static data integrated from multi-source information provided in real-time by the ship navigation situation perception system. This includes information such as the ship's position, speed, course, dimensions, and the relevant information of surrounding target ships.

The rule base contains various collision avoidance rules and experiences, such as the International Regulations for Preventing Collisions at Sea (COLREGs), as well as heuristic rules summarized from a large number of actual navigation experiences. For example, rules regarding the priority of avoidance actions that the own ship should take in different encounter situations, and rules about the safe distance that ships should maintain under specific visibility conditions. The model base contains mathematical models used for calculating the motion elements of the target ship, assessing the collision risk level, and solving collision avoidance decision-making schemes [4]. For example, the Kalman filter model is used to predict the motion state of the target ship, and a collision risk assessment model is established to calculate the degree of collision risk between the own ship and the target ship.

The machine learning adopts an integrated learning strategy under the guidance of learning by instruction, including multiple learning methods. Heuristic rule-based reasoning conducts reasoning based on the heuristic rules in the rule base, deriving reasonable collision avoidance decisions from the known environmental information and rules. Analogy-based reasoning, based on rule matching, when encountering a new navigation scenario, matches it with the existing cases in the rule base, finds similar cases, and draws on their collision avoidance decisions. Hybrid reasoning based on rules and examples combines the advantages of rule-based reasoning and example-based reasoning to improve the accuracy and adaptability of decisions. Heuristic search-based reasoning in variable time-space, in a complex navigation environment, uses heuristic search algorithms to find the optimal collision avoidance decision-making path. Approximate reinforcement learning learns through continuous trial-and-error, which actions can obtain the maximum safety benefits in different environments, thereby optimizing the collision avoidance decision. Through these learning methods, the collision avoidance experience database can be continuously updated and improved, enhancing the adaptability of the algorithm to different navigation scenarios.

3.2. Quantitative model

The parameters of the ship's motion state in the automatic collision avoidance geometric model under different situations are as follows:

The first is the automatic collision avoidance geometric model in a head-on encounter situation:

When two ships are in a head-on encounter situation, let the speed of the own ship be V_1, the course be θ_1, the speed of the target ship be V_2, and the course be θ_2. The relative speed V_1 of the two ships can be expressed by formula (1) [5]:

$$V_r = \sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos(\theta_1 - \theta_2)} \tag{1}$$

The relative bearing angle α of the two ships is expressed by formula (2):

$$\alpha = \arctan\left(\frac{V_2\sin(\theta_2 - \theta_1)}{V_1 - V_2\cos(\theta_2 - \theta_1)}\right) \tag{2}$$

Let the initial distance between the two ships be D_0. According to the relative speed and the relative bearing angle, the distance $D(t)$ between the two ships after time t can be predicted by formula (3) [6]:

$$D(t) = D_0 - V_r t \tag{3}$$

When $D(t)$ is less than the set safety distance threshold D_{safe}, a collision risk is determined to exist. At this time, their ship should take avoidance actions. It can change the relative motion trajectory by adjusting the course Δ_θ, and the course after avoidance is $\theta_1^{'} = \theta_1 + \Delta_\theta$. To ensure the avoidance effect, according to the principles of ship dynamics, the value of Δ_θ needs to meet certain conditions, such as the ship's steering ability limitations.

The second is the automatic collision avoidance geometric model in a crossing situation. In a crossing situation, assume that the motion trajectories of the own ship and the target ship form a crossing angle β. The positions of the own ship and the target ship are 2 and 3, respectively, and their speeds are (x_1, y_1) and (x_2, y_2) respectively. Through coordinate transformation, the motions of the two ships are transformed into the relative coordinate system, and the relative velocity V_T and relative position (x_r, y_r) are calculated [7].

The calculation of the relative velocity V_r is similar to that in a head-on encounter situation. The relative position is [8]:

$$x_r = x_2 - x_1$$

$$y_r = y_2 - y_1 \tag{4}$$

Using the relative velocity and relative position, the position (x_c, y_c) of the meeting point of the two ships is predicted. If the distance between the two ships at the meeting point is less than the safe distance threshold, the own ship needs to take avoidance measures. The position of the meeting point can be changed by adjusting the course and speed. Let the adjusted speed of the own ship be V_1' and the course be θ_1'. According to the ship kinematic equations, the adjusted motion trajectory is calculated to ensure that the ship passes outside the safe distance.

When adjusting the course and speed, factors such as the ship's maneuverability, such as its acceleration and deceleration capabilities and steering response time, are considered. For example, when the ship is turning, its turning angular velocity ω cannot exceed the ship's maximum turning angular velocity ω_{max}, that is, $\omega \leq \omega_{max}$. These constraint conditions are used to ensure the feasibility and safety of the avoidance operation [9].

The third is the automatic collision avoidance geometric model in an overtaking situation. In an overtaking situation, the speed V_1 of the own ship is greater than the speed V_2 of the target ship, and the own ship is located at a certain distance behind the target ship. Let the longitudinal distance between the own ship and the target ship be L, and the lateral distance be S. During the overtaking process, the own ship needs to maintain a safe distance from the target ship, and at the same time consider the optimization of the overtaking time and the overtaking path. According to the speed difference $\Delta V=V_1-V_2$ between the two ships, the time $t_{overtake} = \frac{L}{\Delta V}$ required for overtaking is predicted [10–12]. During the overtaking process, the own ship should maintain a lateral safe distance S_{safe}, and can adjust the course to make the ship travel along a safe overtaking path. Let the course adjustment amount during the overtaking process be Δ_θ. According to the principles of ship kinematics and dynamics, the motion trajectory of the own ship within the overtaking time is calculated to ensure that the safe distance requirement is always met during the overtaking process [13–15]. At the same time, considering that the ship may be affected by external factors (such as wind and current) during the overtaking process, the motion trajectory is corrected in real time to ensure the safety and reliability of the overtaking operation.

4. Simulation test and analysis of the algorithm

4.1. Simulation test environment

Ship navigation simulation software, such as Virtual Ship and AquaSim, is used to construct the simulation test environment. In the simulation environment, different navigation scenarios are set, including different encounter situations (head-on encounter, crossing situation, overtaking), different combinations of ship speeds and courses, and different environmental conditions, such as different wind speeds, wind directions, current speeds, and directions. A real-like maritime navigation environment is simulated to ensure the reliability and effectiveness of the simulation test results. At the same time, the time step of the simulation is set, for example, 0.1 seconds, to guarantee the accuracy of the simulation process.

4.2. Simulation test method

For different navigation scenarios, multiple groups of simulation test cases are designed. Each test case contains specific parameters such as the initial state of the ship, the encounter situation, and environmental conditions. In each test case, the autonomous collision avoidance algorithm is run, and key data during the algorithm operation are recorded, such as the ship's position, speed, course, collision risk level, collision avoidance decision, and re-navigation opportunity. Each group of test cases is simulated multiple times, and the average value is taken as the test result to reduce the influence of random errors.

4.3. Simulation test results

Table 1 shows from the simulation test results that each collision avoidance scheme can effectively reduce the collision risk level under different encounter situations. Scheme 2 performs relatively prominently in reducing the collision risk level, with relatively low collision risk levels in all three encounter situations. There are differences in the collision avoidance time and re-navigation time among different schemes and scenarios. The collision avoidance time and re-navigation time of Scheme 2 are relatively short, indicating that this scheme can complete the collision avoidance operation more quickly and return to normal navigation, which has certain advantages in actual navigation. At the same time, by comparing the parameter changes of different schemes in the same scenario, the impact of different parameter adjustments on the collision avoidance effect can be analyzed, providing a reference for further optimizing the collision avoidance algorithm.

Table 1. Results of the algorithm simulation test

Collision avoidance scheme	Scenario 1 (head-on encounter situation)	Scenario 2 (crossing situation)	Scenario 3 (overtaking situation)
Scheme 1 - course adjustment amount (°)	20	30	10
Scheme 1 - speed adjustment amount (knots, kn)	–2	–1	1
Scheme 1 - degree of collision risk (collision probability)	0.05	0.03	0.02
Scheme 1 - collision avoidance time (s)	30	40	60
Scheme 1 - time for resuming navigation (s)	60	80	120
Scheme 2 - course adjustment amount (°)	25	35	15
Scheme 2 - speed adjustment amount (knots, kn)	-3	-2	2
Scheme 2 - degree of collision risk (collision probability)	0.03	0.02	0.01
Scheme 2 - collision avoidance time (s)	25	35	50
Scheme 2 - time for resuming navigation (s)	55	75	110
Scheme 3 - course adjustment amount (°)	15	25	5
Scheme 3 - speed adjustment amount (knots, kn)	-1	-0.5	0.5
Scheme 3 - degree of collision risk (collision probability)	0.08	0.05	0.03
Scheme 3 - collision avoidance time (s)	35	45	70
Scheme 3 - time for resuming navigation (s)	70	90	130

5. Conclusion

The autonomous collision avoidance algorithm for intelligent ships based on navigation experience proposed in this study realizes the autonomous collision avoidance of ships in complex navigation environments by simulating the collision avoidance decision-making process of human drivers, combining quantitative models and multiple learning strategies. The simulation test results show that this algorithm can effectively reduce the collision risk in different encounter situations and ensure the safety of ship navigation. However, the actual maritime navigation environment is more complex and changeable. Future research can further consider more practical factors, such as communication delays between ships and sensor failures, to optimize and improve the algorithm and enhance its robustness and adaptability of the algorithm.

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Disclosure statement

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