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Autonomous Collision Avoidance Method for Unmanned Surface Vehicle Based on Inland River Collision Avoidance Rules

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Abstract

In order to better solve the problem of collision avoidance of Unmanned Surface vehicles (USV) in the process of navigation in inland rivers and realize the autonomy of USV in the process of operation, this paper proposes an autonomous collision avoidance method of small USV based on the rules of collision avoidance in inland rivers. Firstly, according to the characteristics that the limited width of inland rivers and navigation marks in the water will affect the autonomous collision avoidance of USV, the method of calculating ship collision risk is improved. The collision risk calculation function is established by analyzing the influence of the relative distance, closest encounter distance (DCPA) and closest encounter time (TCPA) on collision risk. The collision avoidance rules of inland river are included in the collision avoidance decision of USV. Secondly, in terms of the choice of collision avoidance actions, according to the flexible operation characteristics of small USV, deceleration, reversing and parking collision avoidance actions are added on the basis of steering collision avoidance. Finally, the simulation experiment is carried out in inland river environment. The results show that the autonomous collision avoidance method can effectively avoid the target ship and guarantee the navigation safety of USV in inland waters. The proposed method can provide theoretical reference for autonomous navigation of USV.

Keywords

Unmanned Surface vehicle; Inland river collision avoidance rules; Collision risk; Autonomous collision avoidance.

1. INTRODUCTION

Unmanned Surface Vehicle (USV) is a kind of small surface boat with certain intelligence and high-speed sailing on the water surface, which is equipped with various functional modules according to the mission requirements, and can complete a series of tasks autonomously or semi-autonomously [1]. USV can complete different tasks by carrying different mission loads, and the characteristics of small size, low cost and strong maneuverability make USV have great potential in many fields. USV is often used in underwater topographic mapping, automated feeding in aquaculture, and measurement of environment and water quality [2-3]. When our team used USV to test sewage outlets on both sides of Taipu River in Suzhou, autonomous navigation routes were set for USV during the operation. However, the autonomous navigation of USV would be affected by ships passing through the waterway and ships parked near the river bank. In order to prevent collision accidents, manual remote control is required to assist the operation when there is a collision risk. In this way, operators need to pay attention to the water surface environment at all times, and it is dangerous for operators to observe the water surface environment in the heading area of the USV in a close range due to environmental constraints. Therefore, in order to achieve complete autonomy of the USV in the operation process and ensure its safety in the operation process, this paper carries out a preliminary study on the autonomous collision avoidance method of the USV in inland river waters. For the future to further improve the autonomous USV collision of inland waters.

Most of the research on collision avoidance of USV is the autonomous collision avoidance method of USV based on the rules of collision avoidance at sea. Wang et al. [4] proposed an algorithm based on path search; Ding Zhiguo et al. Human-ship intelligent collision avoidance decision-making method [5]; Zhou Shuanglin and MEYER et al. [6-7] used deep reinforcement learning (DRL) algorithm to solve the collision avoidance problem of ships in complex encounter situations. Compared with collision avoidance at sea, in the process of autonomous collision avoidance in inland waters, it is necessary to consider the limitations of the waters where the ship is located. Aiming at the problem of collision avoidance in inland rivers, Cheng et al. [8] proposed an early warning method and collision avoidance model based on coordinated collision avoidance actions; Ma et al.[9] Confirmation of collision risk and planning of collision avoidance path; Zheng et al. [10] proposed an auxiliary collision avoidance system for inland river ships to assist ships in collision avoidance during inland river navigation; and the above research on autonomous collision avoidance of USV in inland waters , in the process of USV's autonomous collision avoidance, the inland river collision avoidance rules are not considered, which may easily lead to inconsistent collision avoidance actions, resulting in the occurrence of collision accidents. In response to this problem, Bi Jingqiang et al [11] summarized the inland river collision avoidance rules. and sorting, established a knowledge base, and established an autonomous collision avoidance decision-making system for inland water ships combined with electronic chart technology; Wang Qun et al. [12] adopted a reinforcement learning algorithm, according to the inland river collision avoidance rules, respectively from the state space, action space, reward function And four elements of action selection strategy to build a decision-making model for driving behavior of inland USV. Cheng et al. [13] established an early warning model framework for inland river ship collision risk based on the early warning method. According to the relationship between the distance between the ship and the closest point of approach, the time to reach the closest meeting point, the coordination degree of collision avoidance actions and the collision risk, they proposed This paper proposes a collision risk early warning model for inland water ships based on coordinated collision avoidance actions. The coordinated avoidance process of two ships approaching each other in inland waterways is divided into the process of understanding each other's actions, unifying collision avoidance strategies and coordinating maneuvering actions. The collision risk in the collision phase is quantitatively calculated.

To sum up, the collision avoidance problem of ships in open waters at sea only needs to consider the collision relationship between ships, while the collision avoidance problem of ships in inland waters and restricted waters should not only consider the collision relationship between ships, but also the collision relationship between ships. The collision relationship between the ship and the river bank, water navigation marks and various obstacles in the water should be considered. Although the literature [11-12] made decisions according to the inland river collision avoidance rules in the autonomous collision avoidance process of the USV, it did not consider the collision avoidance due to the collision. The influence of river width and underwater navigation marks on collision avoidance decisions of USV, as well as the choice of collision avoidance actions in situations where steering and avoidance cannot be realized. Aiming at the collision avoidance problem of small USV in the process of inland river operations, this paper proposes an autonomous collision avoidance method for small USV based on inland river collision avoidance rules. The method of collision risk has been improved, and the collision risk calculation function is established by analyzing the influence of the relative distance between the two ships, the distance to the closest encounter (DCPA) and the time to the closest encounter (TCPA) on the collision risk; the inland river collision avoidance rules are included In the collision avoidance decision of USV, and according to the characteristics of small USV compared with large ships, such as flexible manipulation and fast speed change, the collision avoidance actions of deceleration, reversing and parking are added on the basis of steering collision avoidance. Therefore, when the conditions for direct steering and avoidance are not available, the USV can first decelerate, stop or reverse, and then take the steering and avoidance action until it can achieve safe avoidance. Finally, the effectiveness of the method proposed in the article is verified by simulation experiments.

2. AUTONOMOUS COLLISION AVOIDANCE MODEL OF USV

2.1. Confirmation of Safe Heading

The confirmation of the collision target and the selection of the safe course are the keys to the autonomous collision avoidance of the USV. In this paper, the Velocity Obstacle method is used to confirm the collision target and select the safe heading. The autonomous collision avoidance model of the USV is shown in Figure 1. The coordinates of the center position of the own ship are $O_{ship}\left(x_o, y_o\right)$; the target ship is regarded as a circular obstacle area with a radius of R, and the coordinates of its center position are $T_{ship}\left(x_T, y_T\right)$. Suppose the heading and speed of the O_{ship} are φ_O and v_O , and the heading and speed of the T_{ship} are φ_T and v_T. From the position of own ship to the circular obstacle area, draw two tangent lines L_l and L_r , and the middle cone area is the collision area, which is called collision cone. The collision cone is based on the concept of relative speed. If the relative speed of the USV and the target ship is at the boundary of the collision cone, the USV will just pass along the boundary of the circular obstacle area; When the speed is within the collision area, the USV and the target ship are in danger of collision, so set the collision risk calculation flag to 1($VO=1$).If the relative speed of the USV and the target ship is outside the collision area, and there is no danger of collision between the USV and the target ship, set the collision risk calculation flag to 0($VO=0$).According to the geometric relationship of the collision cone in the autonomous collision avoidance model of the USV, when the relative speed direction of the two ships is located at the left and right boundaries of the collision area, the heading of the O_{ship} are φ_{ol} , φ_{or}, and the DCPA and TCPA values between the two ships can be determined. The safe area of the USV's heading during collision avoidance is shown in Figure 2. During collision avoidance, it is necessary to control the USV's heading to be in the safe area to avoid collision accidents.

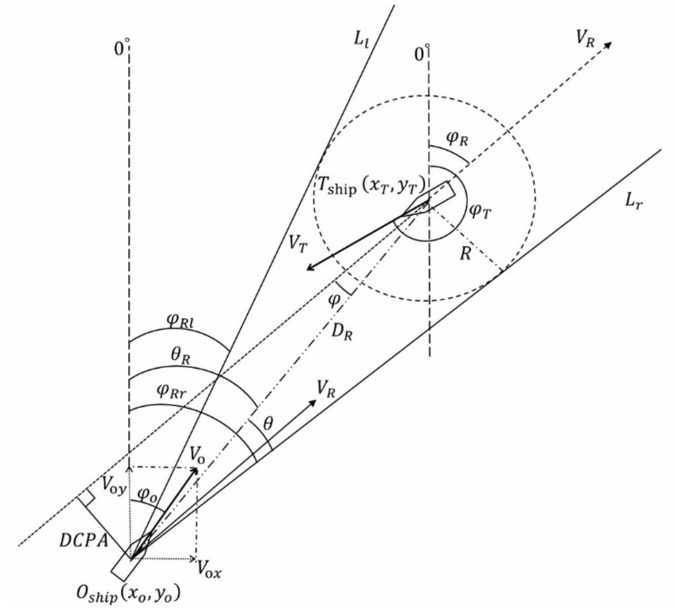


Figure 1. Autonomous collision avoidance model of USV

$$\begin{cases} \varphi_{ol} = \theta_R - \arcsin\left(v_T \cdot \left(\tan\varphi_{Rl} \cdot \cos\varphi_T - \sin\varphi_T\right) \cdot \cos\varphi_{Rl} / v_o\right) - \theta \\ \varphi_{or} = \theta_R - \arcsin\left(v_T \cdot \left(\tan\varphi_{Rr} \cdot \cos\varphi_T - \sin\varphi_T\right) \cdot \cos\varphi_{Rr} / v_o\right) + \theta \\ DCPA = D_R \cdot \sin\left(\varphi_R - \theta_R\right) \\ TCPA = D_R \cdot \sin\left(\varphi_R - \theta_R\right) / v_R \end{cases} \tag{1}$$

D_R is the relative distance between the USV and the target ship, φ_{Rl} and φ_{Rr} are the values of the relative speed direction of the USV and the target ship at the boundary of the collision area, v_R is the relative speed, φ_R is the relative speed direction, θ_R is the relative speed of the target ship to the target ship. The orientation of the USV, θ is the angle between the line connecting the ship and the target ship and the boundary line of the collision area. Its expression is:

$$\begin{cases} D_R = \sqrt{\left(x_o - x_T\right)^2 + \left(y_o - y_T\right)^2} \\ v_R = \sqrt{\left(v_o \cdot \sin\varphi_o - v_T \cdot \sin\varphi_T\right)^2 + \left(v_o \cdot \cos\varphi_o - v_T \cdot \cos\varphi_T\right)^2} \\ \varphi_R = \arctan\left(v_{Rx} / v_{Ry}\right) + \varepsilon \\ \theta_R = \arctan\left(\left(x_T - x_o\right) / \left(y_T - y_o\right)\right) \\ \theta = \arcsin\left(R / D_R\right) \end{cases} \tag{2}$$

Where $\varepsilon = \begin{cases} 0 & v_{Rx} \geq 0, v_{Rx} \geq 0 \\ \pi & v_{Rx} \geq 0, v_{Ry} \leq 0 \text{ J } v_{Rx} < 0, v_{Ry} < 0 \\ 2\pi & v_{Rx} < 0, v_{Ry} \geq 0 \end{cases}$, $\begin{bmatrix} v_{Rx} \\ v_{Ry} \end{bmatrix} = \begin{bmatrix} \sin\varphi_o & -\sin\varphi_T \\ \cos\varphi_o & -\cos\varphi_T \end{bmatrix} \begin{bmatrix} v_o \\ v_T \end{bmatrix}$, v_{Rx} and v_{Ry} are the partial velocities of relative velocity in horizontal and vertical directions.

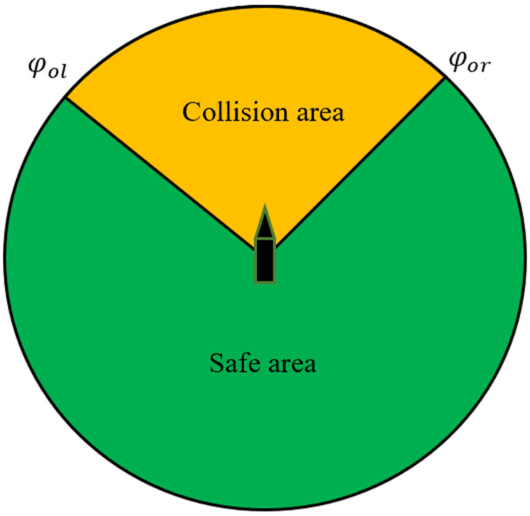


Figure 2. Safe heading area of USV

2.2. Calculation of Collision Risk

Collision risk is an important reference for collision avoidance decisions, Considering that D_R, DCPA and TCPA are the key factors affecting the collision risk of ships in restricted waters, in the risk calculation, the relative distance between the two ships is introduced as the main factor for the collision risk in restricted waters. By analyzing the relative distance between the two ships, DCPA and TCPA The impact on the collision risk, the establishment of the collision risk function.

In previous studies, the collision risk between encountering ships was often calculated based on the values of the closest distance of encounter (DCPA) and the minimum time of encounter (TCPA). However, for narrow waters such as inland rivers, the width of the river is limited, and the relative distance between the upstream and downstream ships is small, but the two sides can still pass through safely, but at this time, the DCPA and TCPA values may have reached the warning threshold. Therefore, it is not sufficient to judge the collision risk between the USV and the target ship only by the values of DCPA and TCPA in inland waters, which may easily lead to inaccurate judgment of the situation, and thus take wrong actions, resulting in the collision between the ship and the target ship. In restricted waters, the variable range of the USV's course is limited by the water area, and the relative distance between the USV and the target ship is the decisive factor for whether the two ships can successfully avoid collision. The relative distance of the target ship is used as the main factor affecting the collision risk of the two ships, and DCPA and TCPA are used as the secondary influencing factors to calculate the collision risk between the USV and the target ship. The smaller the DCPA, the greater the risk of collision between ships, and when the DCPA is less than a certain value, with the decrease of TCPA, the risk of collision between ships will also increase; the relative distance between ships affects the risk of collision between ships The most direct factor, the closer the two ships are, the higher the collision risk between the target ship and the own ship[11]. Functions $y=(ax+b)^{-n}$ (where $a>0$, $b>0$, n are natural numbers) and $y=K^{-cx+d}$ ($K>1$, $c>0$, $d\in(-\infty,+\infty)$) closest to expressing the relationship between DCPA, TCPA and collision risk. The article determines the collision risk calculation function as:

$$Q=\left(D_R/\min D_R+K^{d/n}\right)^{-n}\cdot K^{-(TCPA/\min TCPA+DCPA/\min DCPA-d)} \tag{3}$$

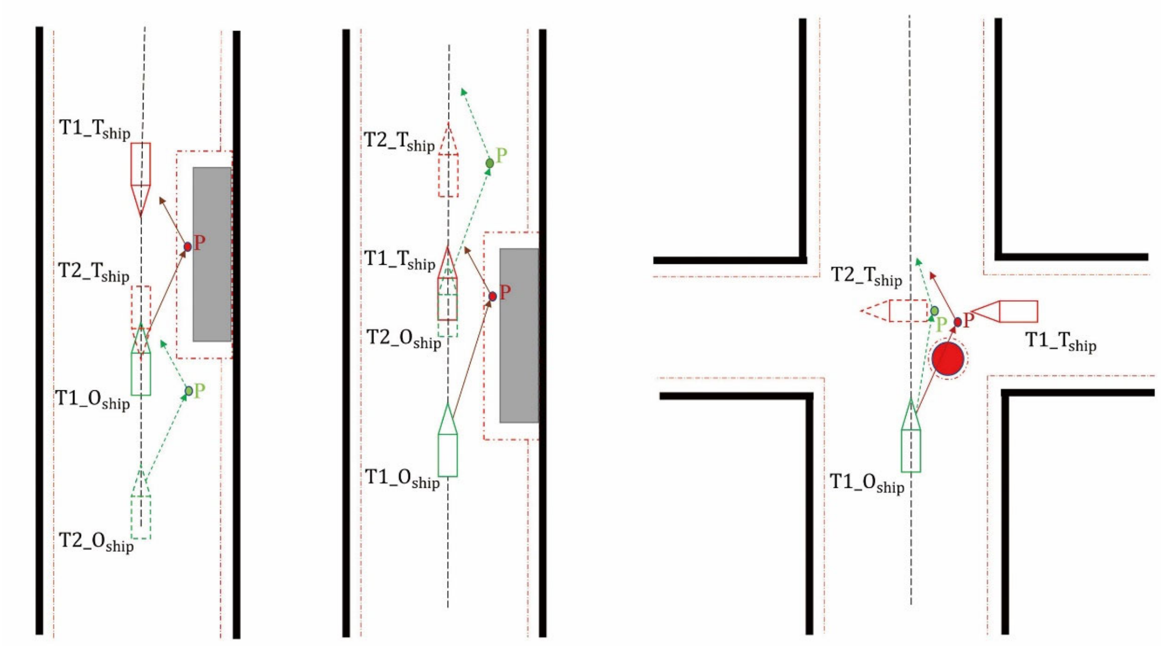
Where, the values of $\min D_R$, d, n, $\min\mathrm{DCPA}$, $\min TCPA$ are determined according to the maneuverability of the USV, $Q\in(0,1]$; the larger the value of Q, the greater the collision risk between the USV and the target ship, when $Q=1$, the USV takes any No collision avoidance action can prevent a collision.

3. AUTONOMOUS COLLISION AVOIDANCE CONSTRAINTS AND DECISION-MAKING FOR USV

The problem of autonomous collision avoidance of USVs in inland waters not only needs to consider the collision avoidance relationship between the USV and the target ship, but also the navigation marks in the river bank and river channel are also the key factors affecting the autonomous collision avoidance decision of USVs.

The three autonomous collision avoidance scenarios of the USV under the constraints of the river bank and the navigation mark distance are shown in Figure 3. First, the safe area of the USV heading during the collision avoidance process can be calculated through the autonomous collision avoidance model of the USV. The safe course selected by the ship calculates the position (x_p,y_p) of the closest encounter point P between the USV and the target ship, and the distances $D_{pt}(x_p,y_p)$, $D_{pr}(x_p,y_p)$ and $D_{of}(x_p,y_p)$ from the target ship, river bank and navigation mark when the USV reaches the point P. If the distances between the USV and the target ship, the river bank and the navigation mark during the process of reaching the point P are all larger than the safe distances R, R_{pr} and R_{of}, then the turning flag is set to 0($RQ=0$), that is, the USV will not interact with the river bank, the target ship and the navigation mark during the avoidance process. When the navigation mark collides, it can directly take the steering and avoidance action. If one of the above conditions cannot be satisfied, the steering flag is set to 1($RQ=1$). The USV does not have the conditions to directly take the steering and avoidance action. At this time, the USV needs to decelerate and stop first. Or reverse, and wait until $RQ=0$ before taking evasive action.

$$\begin{cases} tcpa = D_R \cdot \cos\left(\varphi_{Ro} - \theta_R\right) / v_{Ro} \\ x_p = x_o + tcpa \cdot v_{xo} \\ y_p = y_o + tcpa \cdot v_{yo} \\ D_{pt}\left(x_p, y_p\right) > R \\ D_{pr}\left(x_p, y_p\right) > R_{pr} \\ D_{of}\left(x_p, y_p\right) > R_{of} \end{cases} \tag{4}$$



(a)head-on (b)overtaking (c)crossing

Figure 3. Collision avoidance model of USV constrained by river bank (navigation mark)

3.1. Autonomous Collision Avoidance Decisions for USVs

3.2.1 Judgment of the situation

During the encounter between the own ship and the target ship, the encounter situation of the two ships can be judged according to the headings of the own ship and the target ship. As shown in Figure 4, when the heading difference of the two ships belongs to $\left[165^{d},195^{d}\right]$, the two ships are in head-on situation; when the difference in heading of the two ships belongs to $\left[315^{d},360^{d}\right]J\left[0d,45^{d}\right]$, the two ships are in overtaking situation; otherwise, the two ships are in crossing situation.

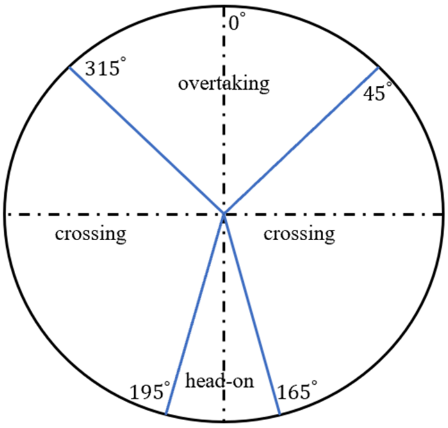


Figure 4. Judgment of encounter situation

3.2.2 Inland water collision avoidance rules

When USV makes collision avoidance decisions, it must abide by the inland river collision avoidance rules [16]. According to the rules for collision avoidance in inland waters, the avoidance relationship between ships in inland waters is shown in Table 1.

Table 1. The relation of avoidance between vessels in inland waters

Encounter situation	Avoidance relationships
head-on	1. The upstream vessel is the giving way vessel and the downstream vessel is the given way vessel 2. In tidal sections, counter-current boats are giving way and down-current boats are being given way
overtaking	1. The pursuing ship shall be the giving way ship, and the pursued ship shall be the giving way ship 2. No chasing or parallel traffic in narrow, curved, beachy sections, bridge waters and lock approaches
crossing	1. The crossing vessel shall be the giving way vessel, and the vessel proceeding down the channel or river shall be the given way vessel 2. When two crossing boats of the same direction of flow cross each other, if there is another boat on the starboard side of this boat, this boat is the giving way boat 3. when two crossing boats of different flow directions meet, the boat going upstream is the giving way boat and the boat going downstream is the given way boat 4. in the tidal section, the upstream vessel is the giving way vessel and the downstream vessel is the given way vessel 5. When two crossing boats meet in a flat current area, the upstream boat is the giving way boat and the downstream boat is the given way boat; when both are upstream or downstream crossing boats, if there is another boat on the starboard side of the boat, the boat is the giving way boat 6. When two boats cross each other in a lake or reservoir and another boat is on the starboard side of the boat, the boat shall give way.

3.2.3 Collision avoidance decision

Through detection technologies such as sensors and precise positioning systems, USVs can obtain information about the USV itself and the target ship, including the position, speed, and heading of the USV, and the position, speed and heading of the target ship. During the encounter between the two ships, according to the information of the USV and the target ship, the speed obstacle method is used to determine whether there is a danger of collision between the ship and the target ship, and the heading difference between the two ships is used to judge the collision between the two ships. If there is a danger of collision between the own ship and the target ship, then use the collision risk calculation function to calculate the collision risk between the own ship and the target ship. When the collision risk between the own ship and the target ship reaches the safe value $\min Q$, the The collision avoidance rules and the constraints of river banks and navigation marks on the autonomous collision avoidance of USVs begin to take collision avoidance actions; when there is a danger of collision between the USV and the target ship, the collision avoidance decision-making process of the USV is shown in Figure 5.

During the collision avoidance process of the USV, the encounter situation of the two ships will not change with the change of the relative orientation and heading of the two ships before the give-way ship passes the clearing. When it is determined that the ship is a direct ship, no action is generally taken. If the collision risk of the two ships reaches an urgent situation and the give-way ship has not taken collision avoidance measures, the ship should take corresponding emergency collision avoidance actions.

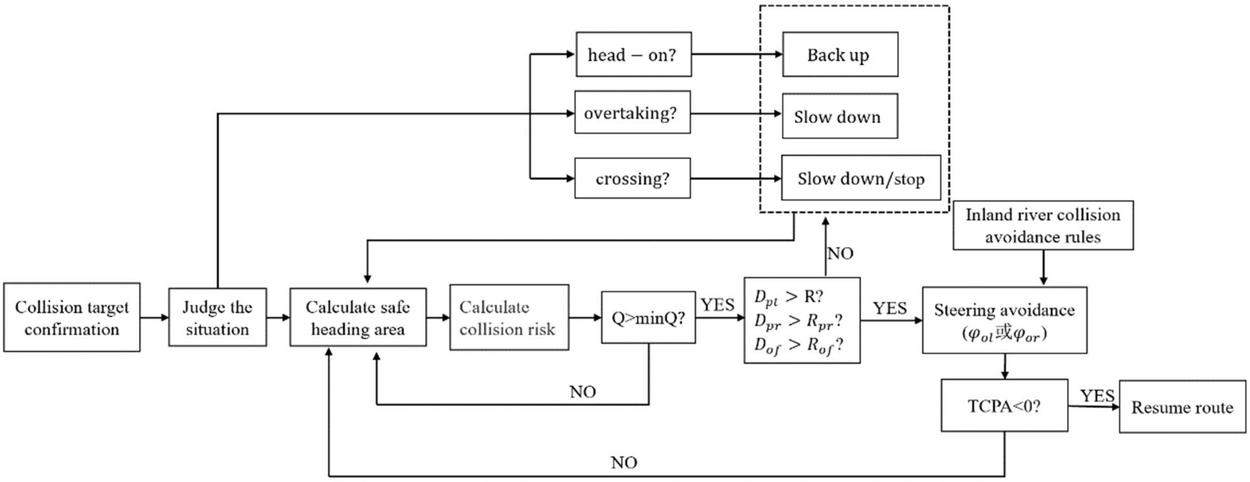


Figure 5. Flow chart of collision avoidance decision

4. SIMULATION

In order to verify the effectiveness of the proposed autonomous collision avoidance method, simulation scenarios are designed from three encounter situations, namely, opposite-driving encounter, overtaking and crossing encounter. Assuming that we have obtained the width of the river channel through the electronic map, we can detect the position and motion information of navigation marks in the water, ships docked near the river bank and obstacles in the water through sensors such as lidar and vision. The obstacle is regarded as a part of the river bank, assuming that the width of the river bank is 40 meters, the safety distance between the two ships is 10 meters, and the initial heading of the USV is 0°, $\min DCPA = 20$ m, $\min TCPA = 30$ s, $\min D_R = 15$ m, $n = 2$, $d = 3$, $R = 10$ m. When the two ships are in the situation of encountering or crossing, assuming that the ship is going up and the target ship is going down, according to the rules of collision avoidance in inland rivers, the ship is a give-way ship. It is necessary to take the initiative to avoid the target ship; in the overtaking situation, assuming that the own ship is the overtaking ship, according to the inland river collision avoidance rules, it can be known that the own ship is the give way ship and the target ship is the given way ship.

4.1. Collision Risk Calculation Function Verification Simulation Experiment

Firstly, the multi-ship encounter simulation experiment is used to verify the effectiveness of the collision risk calculation function and the collision avoidance timing selection method of the avoidance method proposed in this paper without considering the limitations of the river channel and navigation mark. The simulation experiment scene is shown in Figure 6.

In the process of collision avoidance, the encounter situations between the own ship and the target ship are chasing, confrontation and starboard crossing. The collision avoidance decision of own ship is shown in Figure 7. At time T0, own ship turns right to avoid target ship 1 (Tship1); at time T1, own ship returns to the initial course, and at time T2, own ship turns right to target ship 2 (Tship2) to evade; at T3, the collision risk between the ship and the target ship 1 and target ship 2 is eliminated, and the ship returns to the initial route. At time T4, the ship turns to the right to avoid the target ship 3 (Tship3); at time T5, the collision risk between the ship and the target ship 3 is eliminated, and the ship returns to the initial route. According to the rules for collision avoidance in inland rivers, this ship is a give way vessel, and the collision avoidance actions of this ship conform to the rules for collision avoidance in inland rivers.

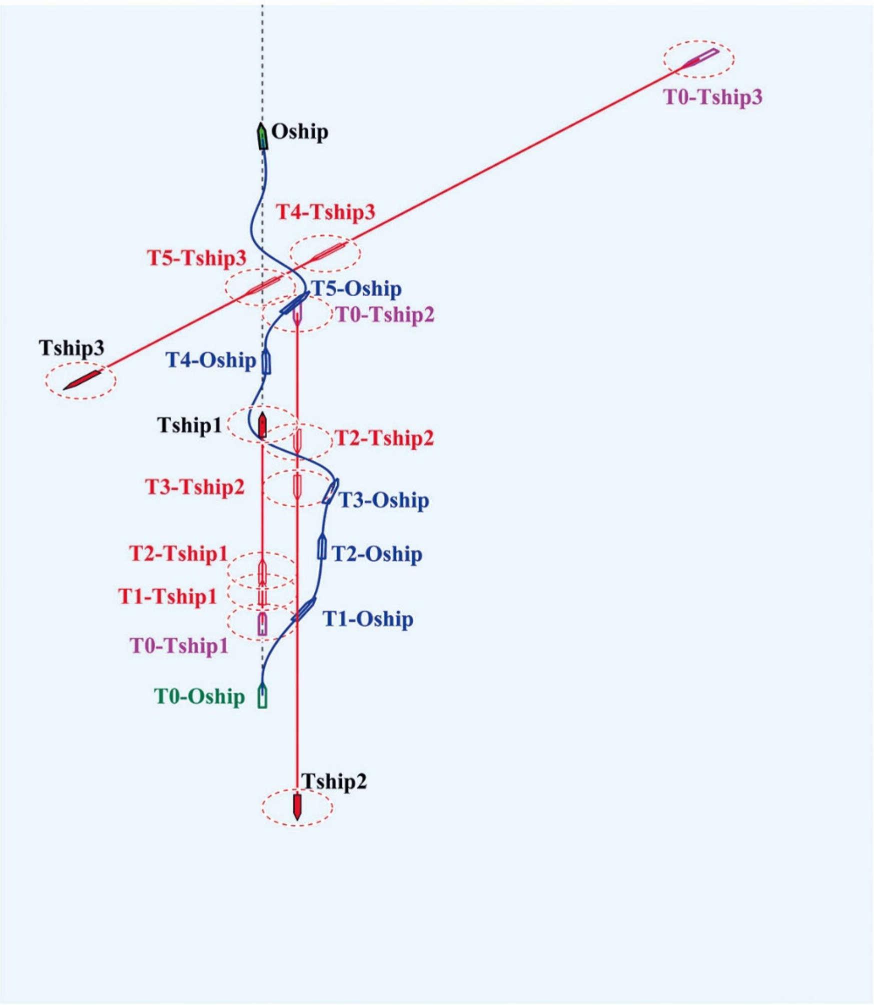


Figure 6. Multiple ships encounter simulation scenario

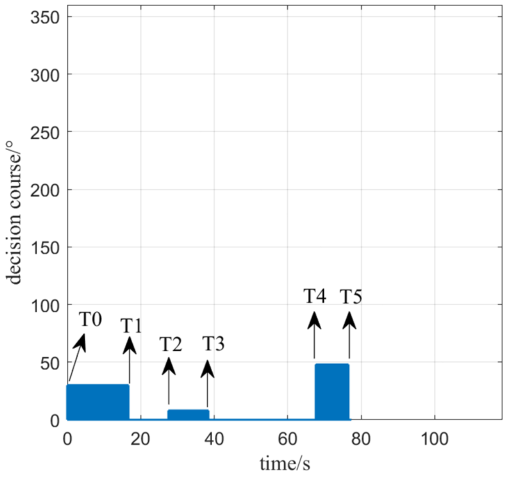


Figure 7. Steering decision of USV

The relative distance and collision risk between the own ship and the target ship are shown in Figure 8. Dr1, Dr2, Dr3 and Q1, Q2, Q3 are the relative distance and collision risk between the own ship (Oship) and the target ship 1, target ship 2, and target ship 3, respectively, q1, q2 and q3 indicate that Oship did not actively avoid the target ship It can be seen from the figure that Oship's autonomous collision avoidance action reduces the collision risk between it and the target ship, and the relative distance between Oship and the target ship is always greater than the safe distance during the collision avoidance process. The experimental results show that the ship can safely avoid the target ship and abide by the inland river collision avoidance rules, which verifies the effectiveness of collision risk calculation and collision avoidance timing selection in the collision avoidance algorithm.

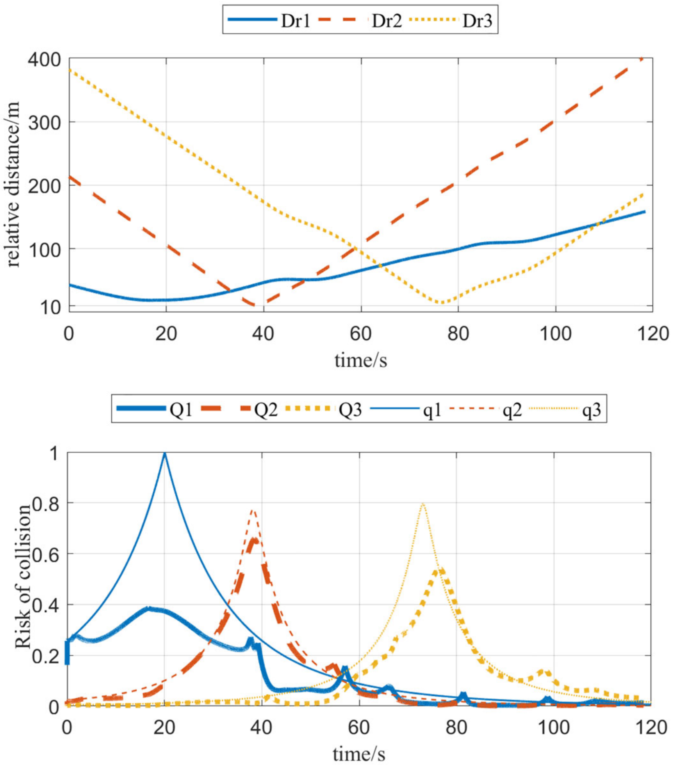


Figure 8. Relative distance and collision risk between USV and target vessel

4.2. Simulation Experiment of Collision Avoidance of Usvs in Inland Waters

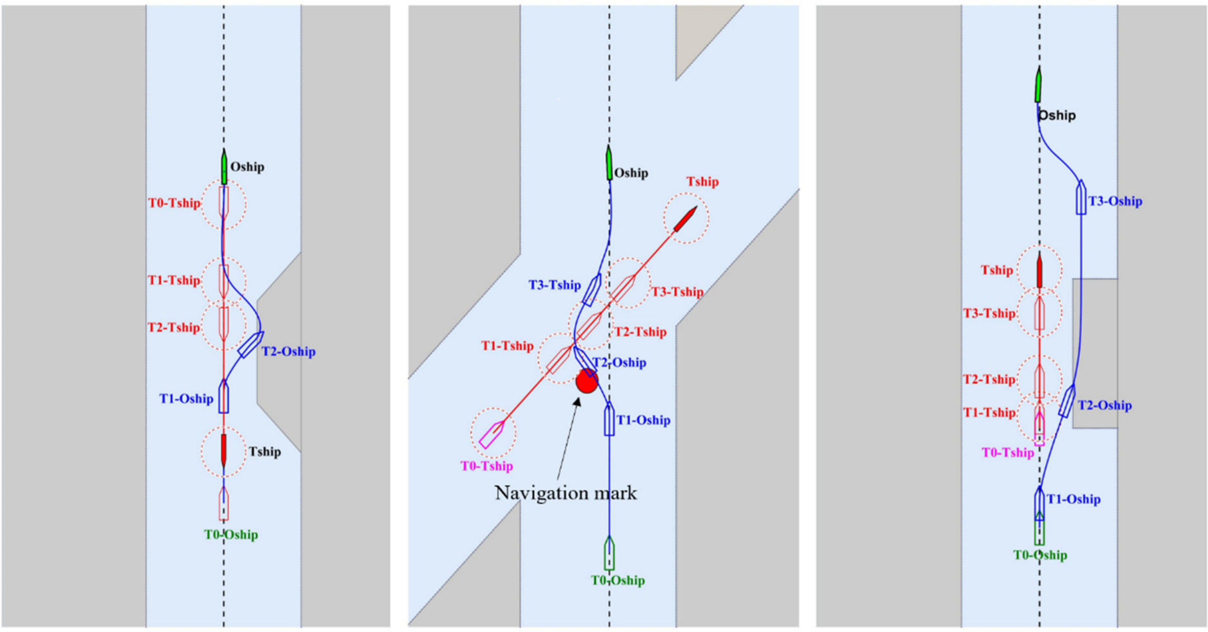
In order to verify the effectiveness of the collision avoidance method proposed in the article in inland waters, the article designs a simulation experiment of autonomous collision avoidance for USVs in three encounter situations: facing encounter, overtaking and crossing encounter. The simulation results of the USV without considering the constraints of the river bank and the navigation mark in the process of collision avoidance are compared with the simulation results considering the constraints of the river bank and the navigation mark. The simulation scenarios are shown in Figures 9 and 11.

In the three encounter scenarios shown in Figure 9, when the collision risk between the USV and the target ship reaches a safe value, the USV directly takes the steering and avoidance action; the parameter changes during the autonomous collision avoidance process of the USV are as follows: shown in Figure 10. In Figure 10, according to the relative distance between the ship and the target ship and the change curve of the distance between the ship and the river bank (navigation mark), it can be seen that when the ship does not consider the constraints of the river bank and the navigation mark in the collision avoidance process, although the target ship can be avoided. , but the ship will collide with the river bank (navigation mark) and cannot achieve safe avoidance of the target ship.

In the three scenarios shown in Figure 11, the steering decision of the USV is shown in Figure 12. In the scenario of encountering in the opposite direction, if the ship directly takes the steering action at T1, it will collide with the river bank, so the ship reverses first; at T2, the ship can safely avoid the target ship and turn right to the target ship. Avoidance; at time T3, the collision risk between the ship and the target ship is eliminated, and the ship returns to the original route. In the cross encounter scenario, if the ship directly takes the steering action at T1, it will collide with the navigation mark, so the ship will decelerate first; at T2, the ship can safely avoid the target ship and turn left to avoid the target ship; At time T3, the collision risk between the ship and the target ship is eliminated, and the ship returns to the original route. In the overtaking scenario, if the ship directly takes the steering action at T1, it will collide with the river bank, so the ship decelerates first; at T2, the ship can safely avoid the target ship and turn right to avoid the target ship. ; At time T3, the collision risk between the ship and the target ship is eliminated, and the ship returns to the original route. According to the rules for collision avoidance in inland rivers, the autonomous collision avoidance decisions of USVs in the three encounter situations are all in line with the rules for collision avoidance in inland rivers.

Under the constraints of the river bank (navigation mark), the parameter changes in the process of autonomous collision avoidance of the USV are shown in Figure 13. According to the speed curve of the own ship, the relative distance between the ship and the target ship, and the change curve of the distance between the ship and the river bank (navigation mark), it can be seen that under the conditions of considering the constraints of the river bank and the navigation mark in the collision avoidance process of the own ship, if there is no direct avoidance When the conditions are met, the ship first decelerates, reverses or stops, and then takes the steering and avoidance action when the ship can safely avoid the target ship. The relative distance between the USV and the target ship and the distance curve between the USV and the river bank (navigation mark) can be It can be seen that the relative distance between the USV and the target ship is always greater than the safe distance during the entire collision avoidance process, and the USV will not collide with the river bank (navigation mark), which realizes the safe avoidance of the USV to the target ship.

In the practical application of USVs, due to the limited width of the river in inland waters and there may be navigation marks in the river, the USV should consider the collision between the USV and the river bank and navigation marks during the collision avoidance process when avoiding the target ship. relation. The paper considers the constraints of river channels and navigation marks in the choice of collision avoidance decision. According to the simulation results, the ship's safe avoidance of the target ship is realized, and the inland river collision avoidance rules are complied with, which verifies the effectiveness of the autonomous collision avoidance method proposed in the article.



(a) head-on (b) overtaking (c) crossing

Figure 9. Simulation scenario of autonomous collision avoidance of USV without river bank (navigation mark) constraints

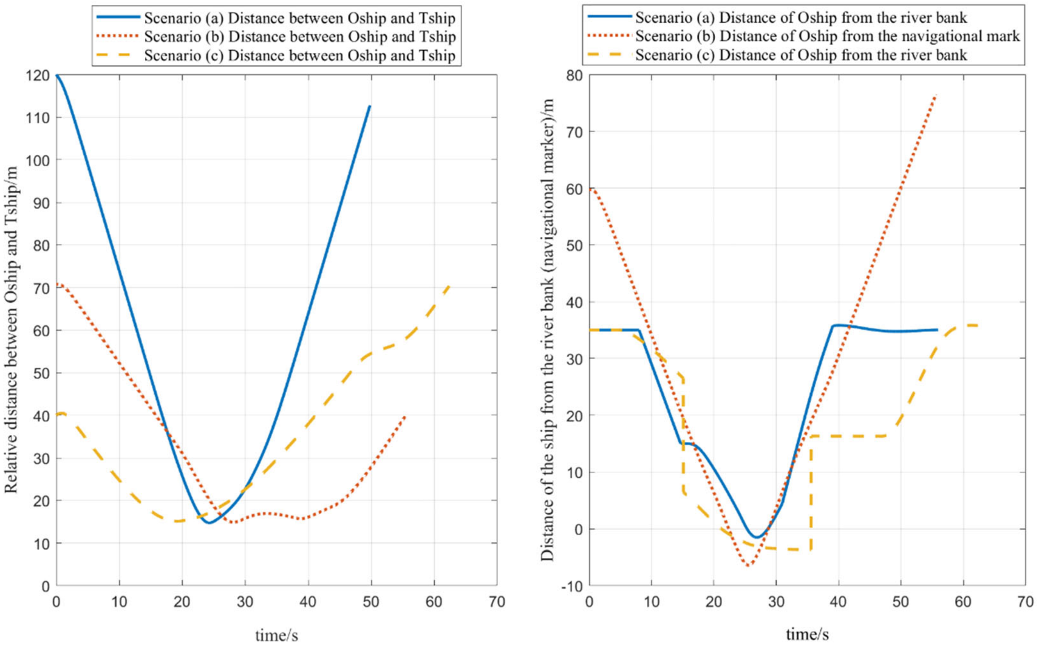
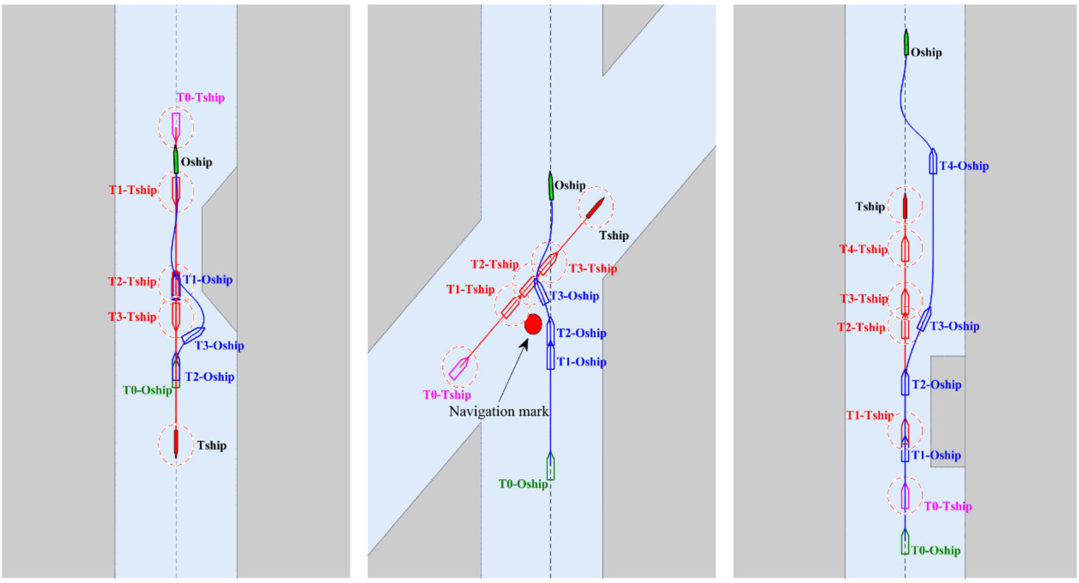
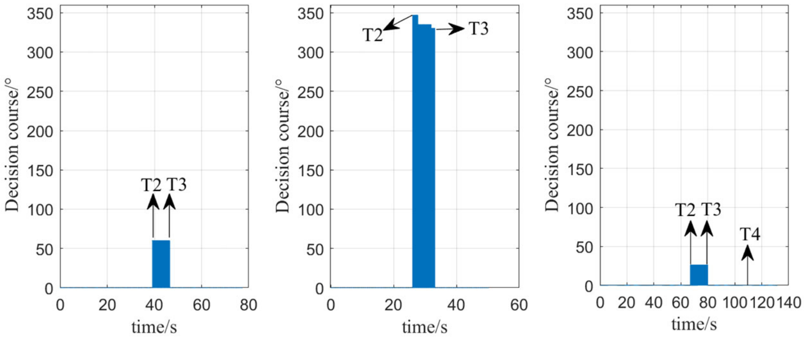


Figure 10. Parameter changes in autonomous collision avoidance of USV without river bank (navigation mark) constraints



(a) head-on (b) overtaking (c) crossing

Figure 11. Simulation scenario of autonomous collision avoidance of USV with river bank (navigation mark) constraints



(a) head-on (b) overtaking (c) crossing

Figure 12. Steering decision of USV with river bank(navigation mark) constraints

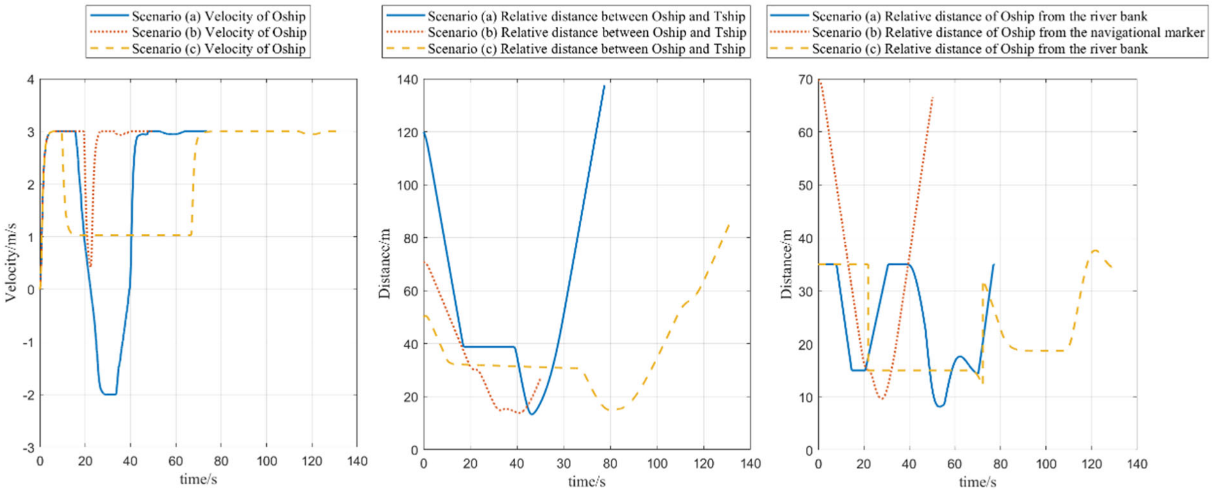


Figure 13. Parameter changes of USV autonomous collision avoidance with river bank (navigation mark) constraints

5. CONCLUSION

This paper proposes an autonomous collision avoidance method for USVs based on the inland river collision avoidance rules. In the process of collision avoidance, the influence of river banks and water navigation marks on the autonomous collision avoidance of USVs is considered, so that the USVs can comply with the collision avoidance rules in inland rivers. In the case of autonomous avoidance of the target ship. Use the speed obstacle method to search for ships that may collide and determine the safe course, then calculate the collision avoidance parameters in real time, and calculate the collision risk between the USV and the target ship. When the collision risk is greater than the safe value, if the USV is avoiding collision During the process, the USV will avoid collision with the river bank or navigation mark, and the USV will evade autonomously according to the inland river collision avoidance rules. If the USV may collide with the river bank or navigation mark during the collision avoidance process, the USV needs to slow down, stop or reverse. , wait until the target ship can be safely avoided, and then avoid the target ship according to the inland river collision avoidance rules. After the avoidance, the USV returns to the initial route and continues to sail, completing the autonomous avoidance of the USV to the target ship. The simulation results show that the relative distance between the USV and the target ship is always greater than the safe distance, which realizes the autonomous avoidance of the USV to the target ship under the premise of complying with the inland river collision avoidance rules, which verifies the effectiveness of the collision avoidance method proposed in the article. effectiveness.

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