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Deliberative Collision Avoidance for Unmanned Surface Vehicle Based on the Directional Weight

*WU Gongxing** (吴恭兴), *SHI Danda* (史旦达), *GUO Jiamin* (郭佳民)
(College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China)

Abstract: The purpose of this study is to realize the intelligent deliberative obstacle avoidance for unmanned surface vehicle (USV), based on the International Regulations for Preventing Collisions at Sea called COLREGS. Firstly, a three-level system architecture is designed for the ship intelligent collision avoidance system. Secondly, an intelligent collision avoidance algorithm is presented based on the calculation of motion parameters and the rules of COLREGS. Thirdly, according to COLREGS, the marine environment is modeled from the electronic chart data and radar information, and a deliberative collision avoidance algorithm is written. Finally, the deliberative collision avoidance simulation is carried out for the USV. The feasibility and reliability of intelligent collision avoidance algorithm are verified by the vivid simulation results.
Key words: ship collision avoidance, deliberative collision avoidance, architecture, visual simulation
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0 Introduction

Due to the development of world economic globalization and integration, water traffic volume rises sharply. According to the statistical data, the number of collision between ships has increased, and can cause significant casualties and property losses[1]. Therefore, the study of ship collision avoidance has a reality urgency. In addition, the research of ship collision avoidance is conducive to ocean research, commercial fishing, ocean survey, weather forecast, development of the marine biological monitoring, and so on[2]. In the military field, unmanned surface vehicle (USV) with collision avoidance system can perform a variety of search and rescue[3-4]. Therefore, it has a great significance to the study of ship collision avoidance problem[5]. In recent decade, the USVs have grown in popularity. In particular, the functions of USVs of automatic obstacle avoidance and conformance with the International Regulations for Preventing Collisions at Sea called COLREGS were posed by Campbell et al.[6] in order to increase the level of autonomy. Zhuang et al.[7] presented a dynamic obstacle avoidance method based on the relative coordinate which complies with the international regulations for preventing collisions at sea. Marco et al.[8] presented a collision avoidance algorithm based on the virtual target path-following guidance technique. Abu-Tair and Naeem[9] presented a practical solution for obstacle detection and the avoidance mainly for USVs. In Ref. [9], an integrated decision support framework could provide risk assessment as an integrated feature to the path planner. In Ref. [10], the collision-free path planning for unmanned surface vehicle was studied by using advanced A* algorithm. Yang et al.[11] presented a path planning method using satellite images for USVs.

This paper makes an effort to design the intelligent deliberative obstacle avoidance system for USV based on the rules of COLREGS. The USV's intelligent collision avoidance system structure is present, in which, the organization, coordination and implementation levels are shown. Finally, the autonomous navigation of vessels is realized in real ocean environment.

1 The System Structure of Ship Intelligent Collision Avoidance

Ship collision avoidance is a collection of all kinds of technologies in the integrated technology, including automatic control, sensor information processing, etc. The ship intelligent collision avoidance system architecture is the key to combine various technical modules and orderly coordination organization together. A three-level system architecture (implementation, coordination and organization) is shown in Fig. 1.

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***E-mail:** wugongxing_163@163.com

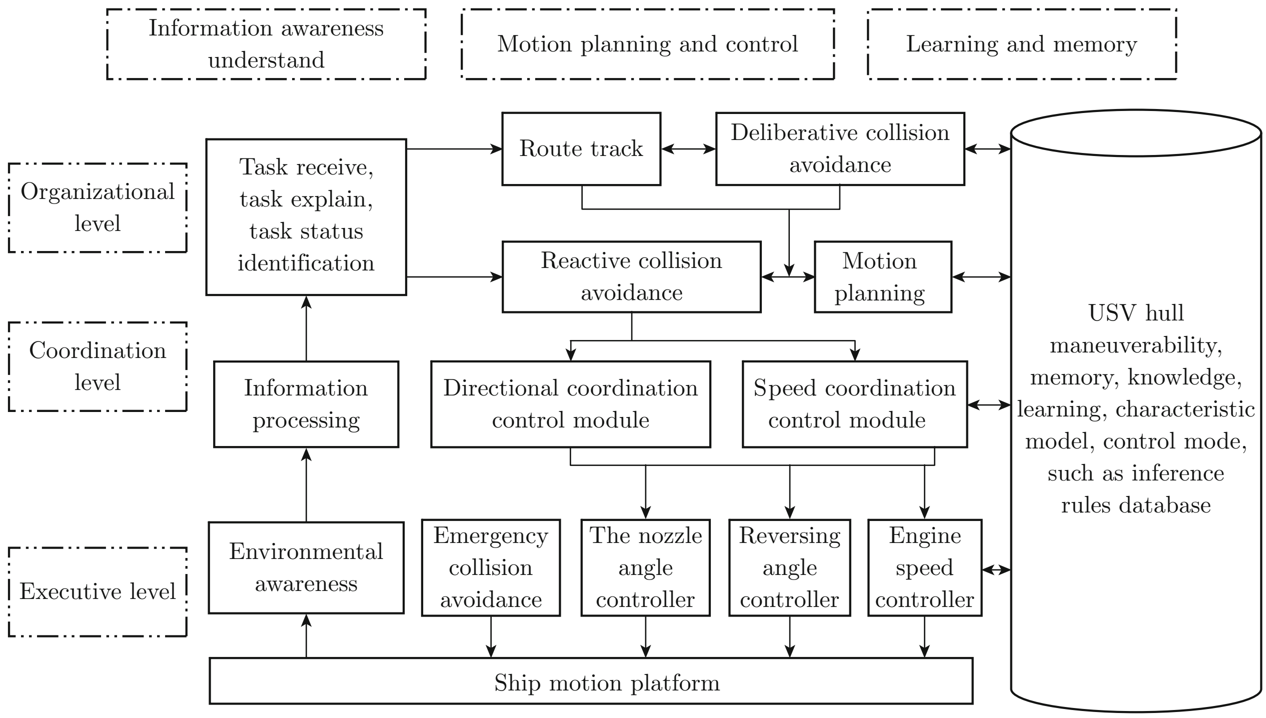


Fig. 1 Ship intelligent collision avoidance control system structure

2 The Ship Intelligent Collision Avoidance Algorithm

According to the distance between the obstacles and the USV, the collision zones can be divided into four zones: safety zone, deliberative collision zone, reactive collision zone, and forbidden zone, as shown in Fig. 2. This paper will present the ship intelligent deliberative collision avoidance algorithm in the deliberative collision zone.

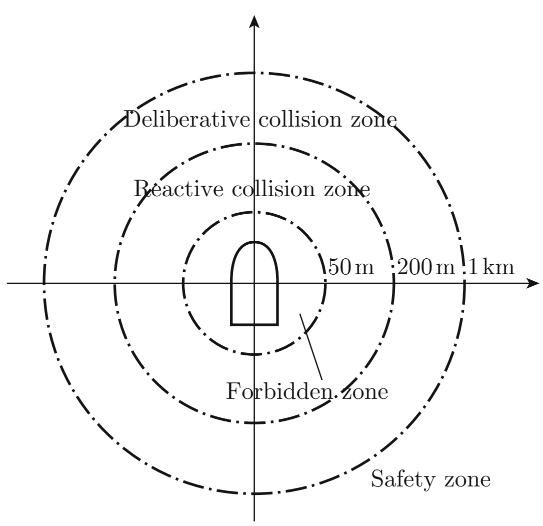


Fig. 2 Ship safety domain model and the collision avoidance zoning

2.1 Calculating the Motion Parameters

In the ship intelligent collision avoidance algorithm, it is important to determine the motion parameters of this ship and the other ship, which is the base of all kinds of calculation and judgment. Therefore, the corresponding conversion should be carried out under the same coordinate system. The following is a variety of ship motion parameters calculation[5].

The speeds of this ship and the other ship on the ship shaft components are

$$\left.\begin{aligned} v_{x_0} &= v_0 \sin\varphi_0 \\ v_{y_0} &= v_0 \cos\varphi_0 \end{aligned}\right\}, \quad \left.\begin{aligned} v_{x_T} &= v_T \sin\varphi_T \\ v_{y_T} &= v_T \cos\varphi_T \end{aligned}\right\}, \tag{1}$$

where $(x_0,\ y_0)$ is the geographical coordinate of this ship S_0 at speed v_0 and heading φ_0, and (x_T, y_T) is the geographical coordinate of the other ship at speed v_T and heading φ_T.

The other ship relative velocities on the x and y axis components can be represented as

$$\left.\begin{aligned} v_{x\mathrm{R}} &= v_{x_T} - v_{x0} \\ v_{y\mathrm{R}} &= v_{y_T} - v_{y0} \end{aligned}\right\}. \tag{2}$$

The magnitude of relative speed is

$$v_\mathrm{R} = \sqrt{v_{x\mathrm{R}}^2 + v_{y\mathrm{R}}^2}.$$

Heading of the relative speed is

$$\varphi_\mathrm{R} = \arctan\frac{v_{x\mathrm{R}}}{v_{y\mathrm{R}}} + \alpha,$$

where

$$\alpha = \begin{cases} 0, & v_{x\mathrm{R}} \geqslant 0, \quad v_{y\mathrm{R}} \geqslant 0 \\ \pi, & v_{x\mathrm{R}} < 0, \quad v_{y\mathrm{R}} < 0 \\ \pi, & v_{x\mathrm{R}} \geqslant 0, \quad v_{y\mathrm{R}} < 0 \\ 2\pi, & v_{x\mathrm{R}} < 0, \quad v_{y\mathrm{R}} \geqslant 0 \end{cases}. \tag{3}$$

Relative distance to other ship is

$$R_T = \sqrt{(x_T - x_0)^2 + (y_T - y_0)^2}.$$

The true bearing of the other ship related to this ship is

$$a_T = \arctan \frac{x_T - x_0}{y_T - y_0} + \alpha. \tag{4}$$

The true bearing of this ship related to the other ship is

$$a_0 = \arctan \frac{x_0 - x_T}{y_0 - y_T} + \alpha. \tag{5}$$

Relative bearing of the other ship is

$$\theta'_T = a_T - \varphi_0 \pm 2\pi.$$

Heading corner of this ship and the other ship is

$$C_T = \varphi_T - \varphi_0.$$

Distance of close point of approaching (DCPA) between this ship and the other ship is

$$\mathrm{DCPA} = R_T \sin(\varphi_\mathrm{R} - a_T - \pi). \tag{6}$$

Time to close point of approaching (TCPA) between this ship and the other ship is

$$\mathrm{TCPA} = R_T \cos(\varphi_\mathrm{R} - a_T - \pi)/v_\mathrm{R}. \tag{7}$$

TCPA being less than zero means that the target ship has already past the closest point of approaching.

The relationship between the close point of approaching and the relative bearing is

$$\theta_T = \begin{cases} \varphi_\mathrm{R} + \pi/2 - \varphi_0, & \mathrm{DCPA} \geqslant 0 \\ \varphi_\mathrm{R} - \pi/2 - \varphi_0, & \mathrm{DCPA} < 0 \end{cases}. \tag{8}$$

According to the position of the detect obstacles from radar, all of the motion parameters are calculated between this ship and the other obstacles ship. This provides the necessary information for the collision modeling and collision avoidance decision-making.

2.2 Deliberative Collision Avoidance Rule

The COLREGS rules are concerned about the lights, warning signal, rule applications, related definitions etc., and don't care about the path planning and collision avoidance problem for USVs. So, in this paper the encounter situation between ships can be summarized as meeting, crossing and overtaking. The rules of three kinds of encounter situation and the navigation rules are defined and also shown in Fig. 3.

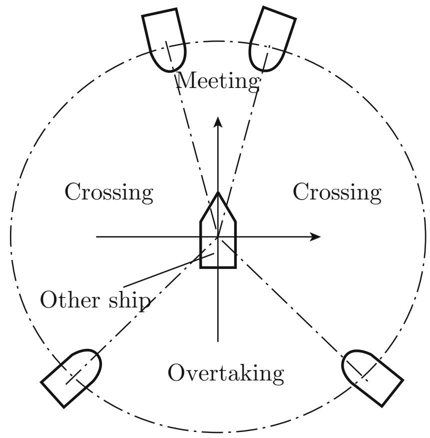


Fig. 3 International regulations for preventing collision marine division of ship encounter

Meeting When two ships navigate relative to each other, collision damage may occur. They are supposed to turn right, and navigate through theirs own port in order to avoid the risk of collision.

Crossing When two ships cross through each other, one ship is in another ship's starboard side, so that the ship should make way and avoid navigating in front of another ship.

Overtaking In condition of any ship overtaking other ship, it is must be out of the way and should pass the ship from its port side.

You can see that the COLREGS rule for ship encounter is very fuzzy. The driver can feel the collision avoidance rules by heart. The encounter situation is divided into six zones in order to make the USV comply with the rules. Firstly, the encounter situation is compartmentalized according to the relative bearing between ships. Secondly, the type of the encounter (such as meeting, crossing or overtaking) is determined by the crossing angle of two encountering ships. Finally, different collision avoidance decision is made according to different encounter type. The encounter situation and navigation rules are shown in Fig. 4.

2.3 Deliberative Collision Modeling

In order to realize the modeling method that can be applied to multi-ship collision avoidance decision-making, this paper adopts the method of true bearing weighted modeling. Before modeling, the true azimuth

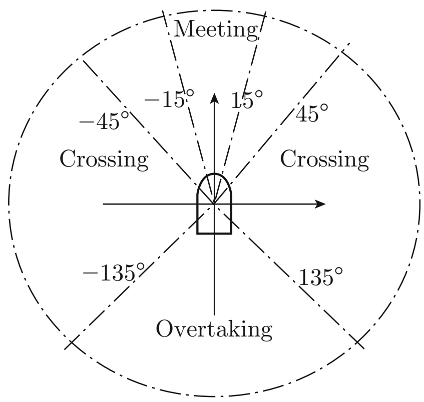


Fig. 4 Ship encounter situation

is divided into 360 equal parts. The factors that affect the USV navigation direction are modeled by a weighted method, such as current waypoint, obstacles motion state, and COLREGS rules. If there are multiple obstacles near the USV, other obstacles or ships are superposition modeled, and all the total weights of true azimuth are calculated. According to COLREGS, the marine environment is modeled from the electronic chart data and radar information, and then the deliberative collision avoidance algorithm is written.

The Current Waypoint Azimuth Modeling In order to make the ship sail as close as possible to course, the weight of the current waypoint azimuth is the largest (set at 90). And the weight of both sides direction of the current waypoint azimuth is gradually decreased, until the weight is reduced to zero, as shown in Fig. 5, where AB line represents current course for USV.

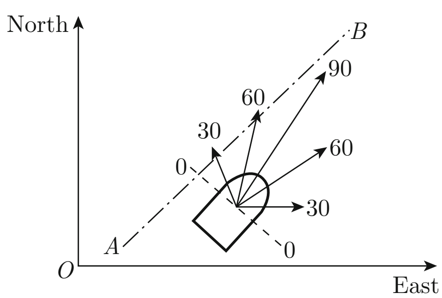


Fig. 5 Current waypoint azimuth modeling diagram

The Obstacle Azimuth and Its Speed Prediction Modeling The weight of the obstacle azimuth should set very small (set at −180) in order to ensure USV avoid collision to an obstacle. And also the weight of prediction obstacle position azimuth is set very low (set at −180). The weight of both sides direction azimuth is gradually increased, until the weight is increased to zero, as shown in the Fig. 6, where the circle represents the obstacle, and the dotted circle represents the predicted position of the obstacle.

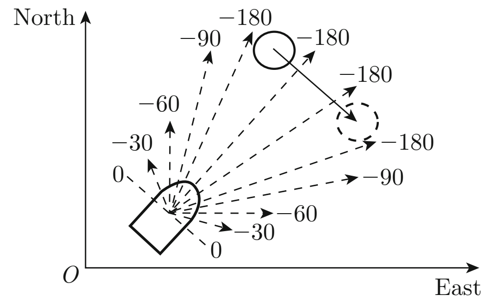


Fig. 6 The obstacle azimuth and its speed prediction modeling diagram

COLREGS Rules Modeling When USV is sailing on the ocean, it needs to comply with the rules of COLREGS. According to the rules of COLREGS, when USV requires a collision avoidance motion, it only needs to turn left or right operation. Therefore, if USV needs to turn left for collision avoidance, then the azimuth weight of its right side is −180, as shown in Fig. 7 and Fig. 8.

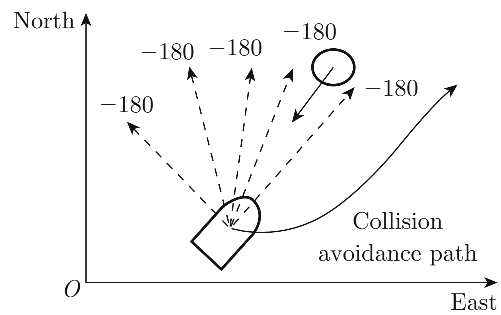


Fig. 7 Right modeling diagram of Marine navigation rules

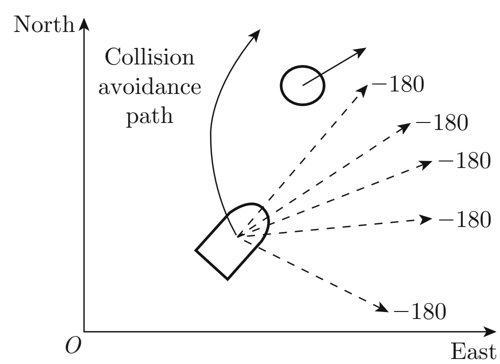
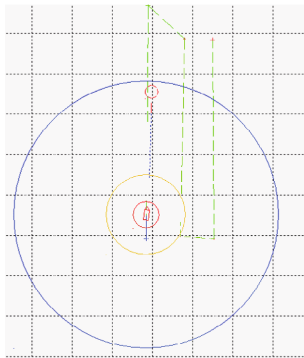


Fig. 8 Left modeling diagram of Marine navigation rules

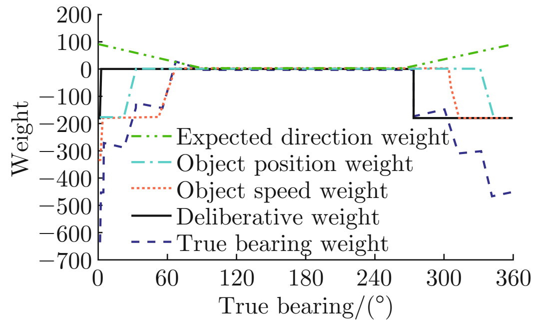
3 The USV Intelligent Collision Avoidance Simulation

The meeting collision avoidance and overtaking collision avoidance are shown in Figs. 9 and 10. According to the idea of deliberative collision avoidance based on

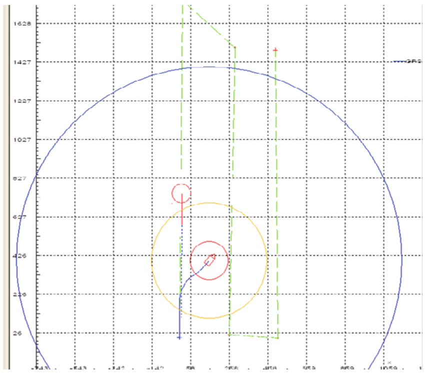
(a) Initial state of meeting collision avoidance



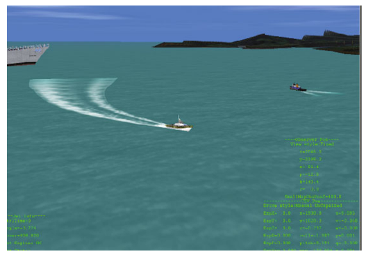
(b) Deliberative meeting collision avoidance



(c) Algorithm weight diagram

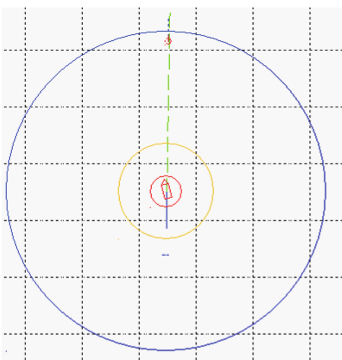


(d) Deliberative meeting collision results

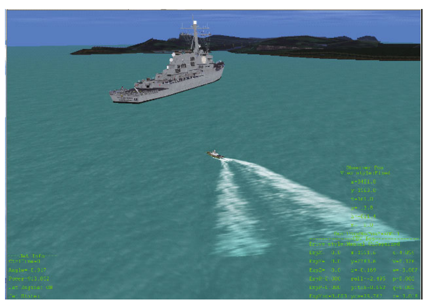


(e) Meeting collision avoidance success

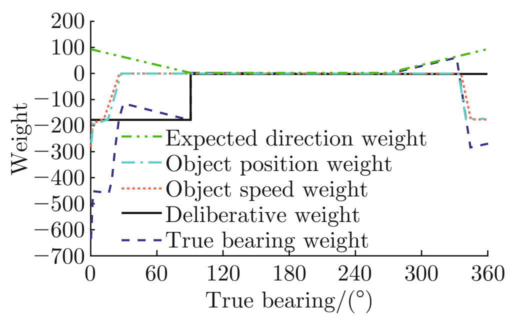
Fig. 9 Deliberative meeting collision avoidance algorithm analysis



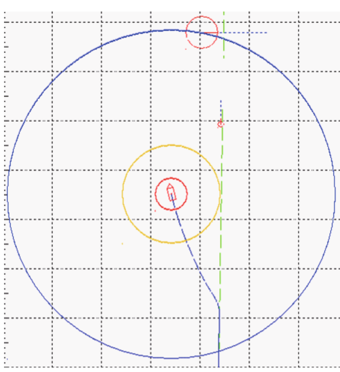
(a) Deliberative overtaking collision avoidance



(b) Initial state of overtaking situation



(c) Algorithm weight diagram



(d) Deliberative overtaking collision results

(e) Overtaking collision success

Fig. 10 Deliberative overtaking collision avoidance algorithm analysis the directional weight, the intelligent collision avoidance simulation system is designed for the USV. And the simulation experiment is undertaken. First of all, the course is set for the USV, and then it sails along the designed course. When USV encounters obstacles (such as other ships or floats), it will steer clear of the obstacles and try to approach the course.

It can be seen that the USV turns to right in the meeting situation. Figures 9(a) and 9(e) show the visual simulation of meeting collision avoidance. Figures 9(b) and 9(d) show the track of USV in two-dimensional plane. Figure 9(c) shows the weight change with the angle of azimuth in 360°.

It can be seen that the USV turns to left in the overtaking situation, which conforms to the COLREGS rules. Figures 10(a) and 10(d) show the track of overtaking collision avoidance. Figures 10(b) and 10(e) show the visual simulation of overtaking collision avoidance. Figure 10 (c) shows the weight change with the angle of azimuth in 360°. The true bearing weight is the sum of the other weights, such as expected direction weight, object position weight, object speed weight, and deliberative weight.

4 Conclusion

In a highly dynamic and unpredictable environment, reliable obstacle avoidance techniques are needed to ensure the safety of the other boats, the people and property. This paper's goal is to make the USV with deliberative obstacle avoidance ability in accordance with the COLREGS rules. From the simulation results of the meeting collision and overtaking collision simulation, it can be seen that the USV can get round the obstacles and follow the COLREGS rules. The intelligent collision avoidance simulation test results show that the collision avoidance algorithm expresses the international regulations very well, and the USV prevents collision of other ships, coast, and all the other obstacles. The vivid visual simulation results show that the algorithm has stronger practicability.

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