Research on Intelligent Collision Avoidance for Unmanned Surface Vehicle with Multi-ship Obstacles Based on COLREGS

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***Abstract*—In order to take into account the International Regulations for Preventing Collisions at Sea (COLREGS) as much as possible, a unified motion model for eccentric expansion of obstacle ships is proposed, which is in accordance with the Convention. To achieve intelligent collision avoidance of multi-obstacless in wide waters, a fuzzy programming method based on the urgency of obstacle avoidance, safety prediction and feasibility of adjustment is proposed. The simulation of collision avoidance planning for multiple complex obstacles with simultaneous encounter, crossover and overtaking conditions proves the intelligence of the method.**

***Index Terms*—unmanned surface vehicle (USV), multi-obstacles, intelligent collision avoidance, convention on the international regulations for preventing collisions at sea (COLREGS)**

I. Introduction

Surface Unmanned Vehicle (USV) is an unmanned autonomous ocean vehicle. It mainly performs tasks in unmanned or dangerous conditions. It will play an important role in ocean exploration, development and utilization, as well as possible future maritime conflicts.

Autonomous collision avoidance of USV means that when USV encounters obstacles such as islands, ships, buoys and other obstacles in the course of sea navigation, it can independently identify obstacles to avoid collision and accomplish specified tasks considering its maneuvering characteristics.

However, due to the characteristics of high speed, complex environment and dynamic obstacles of USV, these algorithms applied to intelligent robots are often difficult to achieve good results. In addition, the speed and angular speed of USV are seldom considered in these decisions, so the planning is often beyond the capability of USV.

People began to study the dynamic collision avoidance algorithm for the motion characteristics of mobile robots long ago, and achieved remarkable research results.

However, the moving environment of unmanned surface craft is more complex and has special maneuverability constraints. Some scholars started the design of unmanned surface craft collision avoidance system based on robot collision avoidance algorithm. The commonly used methods are VFH and its improved algorithm, rolling window method, artificial potential field method and speed obstacle method [1], [2].

In domestic research, Tang Pingpeng proposed a dynamic collision avoidance algorithm, which combines the motion characteristics and basic control characteristics of unmanned surface craft, and achieves collision avoidance through dynamic window method; Ma Chuang based on improved VFH algorithm, used double-deck sonar to build three-dimensional environment model, and carried out collision avoidance design of unmanned surface craft in three-dimensional space through speed obstacles; Relative motion vectors are analyzed to avoid collision of unmanned surface craft; Mao Yufeng establishes the expected velocity solution set for collision avoidance and chooses the optimal solution to achieve collision avoidance; Zudi uses the velocity obstacle method as the basis, and uses the relative velocity change to avoid collision; Chen Huahua uses the neural network to establish the dynamic information environment model, and on this basis uses the fitness function to carry out dynamic collision avoidance; Feng proposed a dynamic collision avoidance algorithm based on acceleration; Zhuang Xiaobo proposed a collision avoidance strategy based on ant colony algorithm for unmanned surface craft [3]-[5].

In the field of foreign research, Jacoby established the obstacle prediction area to predict the movement state of the obstacle and avoid collision by analyzing the position relationship. Aaron proposed a rule-based collision avoidance strategy for unmanned surface craft, formulated different collision avoidance schemes under different circumstances, and selected the best collision avoidance method according to the external conditions and real-time water environment. The method of behavior control framework and interval planning is used to avoid collision dynamically by multi-objectives optimization interval programming. Smierzchalski adopts evolutionary algorithm and genetic mutation algorithm to change ship speed to avoid collision. On this basis, TAM and other dynamic models are combined to adopt evolutionary algorithm to avoid collision dynamically by obstacles. The obstacle avoidance

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method combines local boundary optimization with heuristic A* algorithm [6], [7].

Compared with other intelligent robots, USV intelligent collision avoidance has its own unique rules. COLREGS provides abstract rules for ship collision avoidance at the general level [8], [9]. In collision avoidance planning, USV should consider that obstacle ships generally abide by the Convention, and it should abide by the Convention itself, which has become the consensus of USV intelligent collision avoidance research. The disposal of collision avoidance rules at sea is mostly to subdivide the potential threats into four or seven kinds according to the rules, and then draw up corresponding protocols to build decision-making system for different encounters. As many as 7 or 14 kinds of collision avoidance behaviors may be adopted in the system protocol library. This topological rule structure is too complex, especially in the Multi-ship obstacle environment. At the same time, it is difficult to give correct decision-making; if multiple schemes can be implemented at the same time, it is also difficult to choose among different anti-collision action schemes. In addition, considering the speed obstacle method of rules, conical obstacles are generated in the speed space of unmanned boats, and the risk of collision avoidance in different conical zones is measured by combining the rules of collision avoidance at sea, based on which dynamic anti-collision is carried out in multi-obstacles environments The movement of obstacles considered in the experiment is relatively simple, and they all cooperate actively with unmanned craft to avoid collision or maintain speed. However, a large number of accident investigations show that the non-conformity of ship's traveling path with maritime rules is an important reason for maritime collision accidents. At the same time, most of the algorithms considering collision avoidance rules at sea do not weigh the risk of compliance with the rules. From the perspective of unmanned vessels, collision avoidance strategy is recommended, but because of the uncertainty of obstacle ships, it is possible to make the situation of unmanned vessels more dangerous by forcing collision avoidance strategy under certain circumstances. Therefore, when planning collision avoidance for unmanned vessels, it is necessary to adopt collision avoidance strategy. Considering as many complex and unpredictable obstacle ship paths as possible, the intelligent collision avoidance planning should first satisfy the safety, and then try to satisfy the collision avoidance rules [10].

In view of the existing advantages and disadvantages, this paper argues that a unified and efficient collision avoidance strategy should be established to deal with the collision avoidance rules, which is flexible. That is, the safety of compliance with the rules should be judged, but not blindly observed. The environment should be more realistic. In the complex environment where multiple ships meet at the same time and ship movements change randomly, collision avoidance planning should still be able. Safe collision avoidance, at the same time, collision avoidance planning should also consider whether to meet the maneuverability of USV [11].

In this paper, the eccentric expansion of obstacle ships is carried out according to COLREGS, which increases the obstacles of unmanned vessels violating the convention and gives priority to the direction of collision avoidance in accordance with the rules of maritime collision avoidance. Then, a unified collision avoidance strategy is applied to enable unmanned vessels to determine the direction and speed of collision avoidance according to the collision situation. Meanwhile, the problem of multi-obstacles collision avoidance in wide waters is raised. A fuzzy programming method considering the emergency degree of obstacle ship, the safety of different obstacle avoidance strategies and the feasibility of adjusting obstacle avoidance strategies is proposed. All obstacle avoidance strategies considering maritime rules in complex multi-obstacles environment are selected and the optimal collision avoidance strategy is obtained in real time [12].

II. Maritime Collision Avoidance Rules

In accordance with the Convention on International Rules for the Prevention of Collisions at Sea, the situations in which collision hazards are caused by ship-to-ship interactions are divided into three categories (Fig. 1) [5].

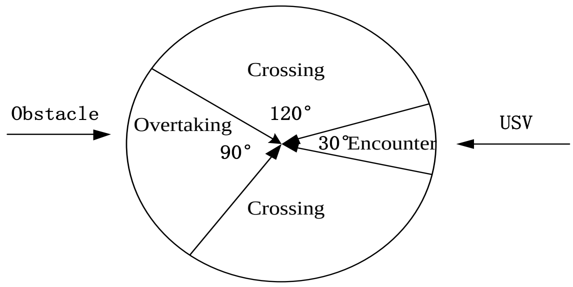

Figure 1. Different situation of COLREGS.

1) Encounter: The heading angle difference $\Delta\theta$ between USV and obstacle ship satisfies $|180° - \Delta\theta| < 15°$, USV should turn to starboard side and pass through port side of obstacle ship.

2) Overtaking: The heading angle difference $\Delta\theta$ between USV and obstacle ship satisfies $|\Delta\theta|<45°$. USV should turn to its port side and pass through the portside of obstacle ship.

3) Crossing: The heading angle difference $\Delta\theta$ between USV and obstacle ship satisfies $45° \leq |\Delta\theta| \leq 165°$, and USV must sail behind obstacle ship.

A. *Eccentric Expansion of Obstacles Complying with Collision Avoidance Rules*

In this paper, the double expansion of obstacle safety and eccentric expansion is used to increase the safety of obstacle avoidance. The eccentric expansion is used to increase the obstacle on the disadvantaged side of maritime rules and to induce unmanned aerial vehicles to conform to the rules of collision avoidance as far as possible when making collision avoidance decisions [13]-[16].

1) Safety expansion of obstacle ships

Safety expansion radius $R' = 1.2R + R_a$, R is collision radius; R_a is domain radius of USV.

2) Eccentric expansion of obstacle ship

Constructing the motion model of USV and obstacles. R is the position of USV and the obstacle is the circle O. So the radius of obstacle is safety expansion radius R'. The speed of USV is (v_R, a), and the speed of obstacle ship is (v_O, α).

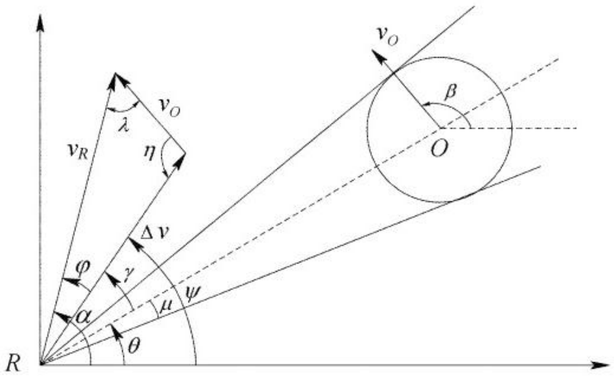

Figure 2. USV and obstacle motion model.

DCPA and TCPA are used to judge the expansion risk of eccentric expansion of obstacles.

$$\begin{cases} DCPA = |RO|\sin(|r|) \\ TCPA = |RO|\cos(|r|/|\Delta v|) \end{cases} \quad (1)$$

Comprehensive collision risk:

$$\mu = \min(\frac{\mu_{DCPA}+\mu_{TCPA}}{2}, 1) \quad (2)$$

μ_{DCPA}、μ_{TCPA} is risk membership function.

Eccentric expansion radius of obstacles based on maritime rules:

$$R^* = 3R'\left\{1 + \frac{2}{3}\sin[\frac{\pi}{2}(\mu + 2)]\right\} \quad (3)$$

R* is 1-3 times R'. When the collision risk is low, the eccentric expansion of obstacles is larger, which has great influence on the collision avoidance rules. When the collision risk is high, the eccentric expansion of obstacles is smaller, and the impact on the collision avoidance rules is small.

Fig. 3 shows that the eccentric expansion circle O* and the safety expansion circle O' are tangent to the circumferential side recommended by the maritime rules, so when R*R', the center of the circle does not coincide. The eccentric expansion circle center:

$$\begin{cases} O^*(x) = O'(x) + (R^* - R')\cos\zeta \\ O^*(y) = O'(y) + (R^* - R')\sin\zeta \end{cases} \quad (4)$$

$$\zeta = \begin{cases} \psi + \frac{\pi}{2}, \text{Encounter} \\ \psi - \frac{\pi}{2}, \text{Overtaking} \\ \psi \oplus \frac{\pi}{2}, \text{Crossing} \end{cases} \quad (5)$$

Among them, ψ is the angle of the closing velocity Δv; when Δv turns to v_0 with a high arc, if it is counterclockwise $\oplus$ is +, if it is clockwise $\oplus$ is-.

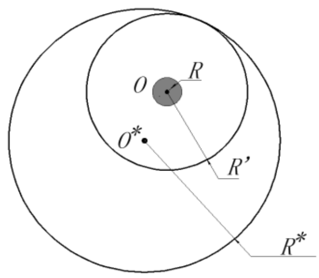

Figure 3. Obstacle and its two-stage expansion.

For the same obstacle ship, unmanned aerial vehicle has different encounter situation on the sea or the same encounter situation. But when the relative position and speed of unmanned aerial vehicle and obstacle are different, DCPA, TCPA and collision risk will be changed, even eccentric expansion circle radius and expansion direction will be changed [17]-[19].

III. Collision Avoidance Strategies for Single Obstacle

The collision avoidance planning still considers the motion model of unmanned and obstacle ships in Fig. 2. The center of the obstacle circle is O*, and the radius is R*. And the eccentric expansion circle is adopted. For each obstacle vessel, if $abs(\gamma) \le \mu$, the collision between the unmanned vessel and the obstacle vessel is possible, where γ is the angle between the combined velocity v and RO. From the geometric relation we can see that:

$$\gamma = \tan^{-1}\frac{v_R\sin(\alpha-\theta) - v_0\sin(\beta-\theta)}{v_R\cos(\alpha-\theta) - v_0\cos(\beta-\theta)} \quad (6)$$

After calculus：

$$\Delta\gamma = \frac{\sin\varphi}{\Delta v}\Delta v_R + \frac{v_R\cos\varphi}{\Delta v}\Delta\alpha + \frac{-\sin\eta}{\Delta v}\Delta v_0 + \frac{v_0\cos\eta}{\Delta v}\Delta\beta \quad (7)$$

On the basis of obstacle velocity v_0, angle β and velocity change Δv_0 and angle change $\Delta\beta$, $\Delta\gamma$ can be changed by adjusting vessel velocity v_R and angle α.

Optimal obstacle avoidance scheme:

$$\begin{cases} \Delta\gamma \ge \mu - \gamma, \gamma \ge 0 \\ \Delta\gamma \le -\mu - \gamma, \gamma < 0 \end{cases} \quad (8)$$

Worst Avoidance Scheme:

$$\begin{cases}\Delta\gamma \le -\mu - \gamma, \gamma \ge 0 \\ \Delta\gamma \le \mu - \gamma, \gamma < 0\end{cases} \quad (9)$$

To avoid a single obstacle, the optimal Δv_R and $\Delta\alpha$ at any time can be solved by the above equation, and the solution can be obtained by means of population optimization algorithm.

IV. Multi-Obstacles Collision Avoidance Strategy

When multiple obstacles have collision risk with USV, the complexity and danger degree of obstacle avoidance increase significantly. Because all online obstacles have direct collision avoidance risk for USV, the significance of DCPA is not so important. The urgency of obstacles is judged only by TCPA. Two online obstacles with the highest urgency are selected for collision avoidance strategy planning. Because the collision situation is updated periodically, it is tight. Online barriers with low degree of compulsion may become offline barriers, or the degree of urgency may increase. Because of the importance of USV collision avoidance strategy, the urgency of obstacles with high urgency may be reduced. Therefore, although only two online obstacles with the highest urgency are considered, in fact, due to periodic updates, obstacle avoidance of all obstacles is considered [20].

A. Variable Speed and Directional Motion with Multiple Obstacles

The starting position of USV and obstacle is the same as the preceding example, but the obstacle has unexpected turning and speed in the course of movement, which tests the intelligent collision avoidance ability of USV. It can be seen that although the movement of obstacle is more complex, the obstacle avoidance strategy in this paper is periodic rolling real-time obstacle avoidance, planning for the current situation of collision at every moment, the speed or direction of obstacle sudden. Sequential changes are considered in each cycle, avoiding obstacles that conform to safety rules, and ultimately arriving.

V. Conclusion

In this paper, eccentric expansion obstacle is carried out according to the rules of collision avoidance. Whether the strategy of collision avoidance is carried out and whether the parameters of collision avoidance are handed over to the collision avoidance planning is carried out in a unified way. A method combining fuzzy decision-making with rule base is proposed to solve the problem of multi-obstacles collision avoidance. The simulation results of MATLAB software show that the intelligent algorithm of multi-obstacles collision avoidance It meets the requirements of the Convention and avoids collision reasonably in complex multi-obstacles environment. The speed limit, speed increase and steering ability of USV are considered, but the execution force of USV control system and the influence of environmental disturbances such as wind, wave and current are not considered.

Conflict of Interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Author Contributions

Ao Wang conducted the research and analyzed the data and wrote the paper.

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Ao Wang has been engaged in the research of unmanned ship motion control for a long time, and has a strong interest in the research of unmanned ship related technology.