Article

Optimized Dynamic Collision Avoidance Algorithm for USV Based on Improved Dynamic Window Approach

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Abstract: Ship collision avoidance is a complex process, influenced by numerous factors. In this study, a new criterion was developed for assessing when USV should take which actions to avoid collisions, called the optimal collision avoidance point method (DWOV). The DWOV based on combining the dynamic window approach and the velocity obstacle method is proposed for the USV from the perspective of the highest probability of collision avoidance. The method calculates the change in the navigation state of the USV based on the critical condition of collision avoidance. The model first calculates the coordinates of the optimal collision avoidance point in the current ship encounter state based on the relative velocity and the kinematic parameters of the USV and the obstacles. Then, the increment of the vessel's linear velocity and heading angle that can arrive at the optimal collision avoidance point is set as a constraint of the dynamic window sampling. Finally, the algorithm evaluates the probability of collision hazard for trajectories satisfying the critical condition and uses the collision avoidance probability value as an evaluation criterion to assess the course. The evaluation results select the corresponding optimal velocity command. Through simulation experiments, the degree of collision avoidance hazards of three different algorithms under different encounter states are compared, and the differences between them are also discussed. The results validated the feasibility and validity of the DWOV algorithm in avoiding dynamic obstacles lower than the maximum velocity of USV.

Keywords: collision avoidance; velocity obstacle method; trajectory optimization; optimal collision avoidance point; dynamic window approach

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1. Introduction

Ship collision is an imperative task for navigation safety at sea. [1]. Unmanned Surface Vehicle (USV) is a light intelligent surface-carrying unmanned equipment with small size, low cost, fast speed, and strong maneuverability[2]. Autonomous obstacle avoidance is one of the core technologies of USV's autonomous navigation capability[3]. USV's collision avoidance algorithm can be considered a local path planning algorithm. This paper focuses on local path planning methods. Many local path planning algorithms were reported for collision avoidance against static and dynamic obstacles [4], [5]. By now, many obstacle avoidance algorithms have been proposed by international scholars, all of which rely more or less on global path planning and mapping, such as bug algorithm[6], vector field histogram method[7], artificial potential field method[8]. Many improved heuristic algorithms have also been studied for local path planning. For instance, a hybrid adaptive path planning scheme based on global path planning and local dynamic collision avoidance for unmanned surface vehicles under complex marine environments was proposed [9]. This method systematically considers the impact of waves and currents on the navigation of the USV. In recent years, some scholars have emphasized the dynamic collision avoidance of ships by incorporating methods such as reinforcement learning and COLREGS[10]. Through the literature statistics, 56% of the collisions at sea are caused by the violation of

COLREGS by ships[11]. However, data is difficult to collect in real-time and the model is difficult to show with mathematical formulas, incorporating regulations in collision prevention algorithms is still a challenge [12]; some scholars have tried the design of ship navigation safety domain to solve the ship collision problem[13],[14],[15]. But most of them only consider static obstacles or semi-dynamic obstacles that do not change in the course [16][17]; highly ideal motion model is used in collision avoidance [18]; Some collision avoidance studies ignored balance efficiency and effectiveness[19].

Some other researchers have evaluated the generated collision avoidance trajectories from the perspective of risk assessment[20], using multiple parameters such as navigation risk[21], navigation smoothness, and other metrics. For instance, review[22] described the collision risk assessment, but it neglected the techniques for conflict resolution; the most frequently used distance parameter for conflict detection and obstacle avoidance is the distance to the closest point of approach d_{cpa}, the time to the closest point of approach t_{cpa} is often used with it. It has been proposed that various techniques can be developed to overcome the limitations of d_{cpa} and t_{cpa} alone for collision avoidance[23]. In[24] and [25], the authors discussed ASV developments in depth, while conflict detection and obstacle avoidance received a lesser amount of attention; only a few studies related to reacting collision avoidance for unmanned ships were included in paper[26].

Compared with other obstacle avoidance algorithms, there are local path planning methods considering kinematics and dynamics constraints. Fox et al. reported the dynamic window approach (DWA) [27], which has become a popular academic research method in recent years. It has been mainly used for navigation and obstacle avoidance in a dynamic environment. Avoiding unpredictable obstacles can better solve the DWA[28]. Scholars have worked on in-depth work based on the DWA for the past few years, which is widely used in dynamic obstacle avoidance path optimization of UAV, robots, and USV[29][30][31]. Dobrevski reported local path planning based on DWA and deep reinforcement learning to improve path optimization [32]. Liu developed the global dynamic path planning fusion algorithm combining jump-A* algorithm and DWA [33]. In addition, several useful local path planning methods based on DWA were reported [34]. However, DWA generates path candidates by assuming constant velocities for a certain period of time. Due to the small distance between obstacles and USV, unexpected collisions often occur during encounters, which makes it challenging to fulfill the safety requirements of USV. However, DWA generates path candidates by assuming constant velocities for a certain period, making it easy to fall into local optimum[35]. In the path evaluation stage, it relies heavily on the setting of the parameter values range. For example, when the distance between an obstacle and a USV is small, accidental collisions often occur during the encounter, which is a challenge to meet the safety requirements of the USV. In addition, the increased complexity of the application scenarios and environments of unmanned devices will make standard DWA unable to solve complex path planning problems. Traditional DWA focuses on path generation at each step of the planning process but ignores that obstacles are also intelligent agents that generate abrupt behavior[36].

Therefore, this paper proposes a dynamic collision avoidance algorithm based on a threshold point. The Optimal Collision Avoidance Point is the threshold point that the algorithm must cover in the trajectory window, which is the unit time generated if the motion state of the encounter can reach that value at the time. Based on the dynamic model of USV, the improved Dynamic Window Approach and Velocity Obstacle algorithm are used to combine the dynamic changes of distance d_{cpa} and time t_{cpa} to calculate the coordinates of the optimal collision avoidance point and the collision avoidance strategy that should be adopted by this vessel arriving at this location, by evaluating the cumulative collision hazard probability value of the trajectory samples generated through this point. Finally, the USV is guided to avoid the obstacle along the optimal trajectory with the lowest cumulative collision hazard probability value.

The contents of this paper are as follows. Section 2 describes the USV dynamic model, the classification of encounter situations, and the basic process framework of USV collision avoidance decision-making in this study. Section 3 contains a detailed description of the optimal timing point model for collision avoidance based on the improved DWA, and we propose a collision avoidance algorithm based on the velocity obstacle method. In Section 4, the results of computational experiments performed for the evaluation of the proposed algorithm are presented. According to simulation experiments, we compared the effects of three different algorithms on the collision avoidance path selection of USV and analyze the degree of excellence resulting from the influence of various collision avoidance factors in path selection. Finally, in Section 5, the conclusions are discussed.

2. USV dynamic system

The Nomoto model, also known as the transfer functional mathematical model, represents the motion of the USV, which is valid in both classical control theory and intelligent control and is used to analyze the dynamic behavior of USV motion in this paper[37].

2.1. USV dynamic model

Figure 1 shows a schematic description of course angles, heading angles, and sideslip angles of the USV dynamic model. As shown in this coordinate frame, where x_i and y_i represent north and east directions, respectively, while v, ν, and V represent surge, sway, and full speed of the vehicle in a body fixed frame, respectively[38]. Next, several essential angles definitions are explained.

Definition 2.1. (course angle θ). In the absence of currents, this is the usual course angle defined from the x-axis of the North-East-Down (NED) frame to the velocity vector V of the vehicle, positive rotation about the z-axis of the NED frame using the right-hand screw convention. In the presence of currents, angles are defined based on the vehicle's relative velocity to the water, which is its total inertial velocity minus the current velocity.

Definition 2.2. (Heading (yaw) angle ψ). The angle from the NED x-axis to the body x-axis, positive rotation about the z-axis of the NED frame by the right-hand screw convention.

Definition 2.3. (Sideslip (drift) angle χ). The angle from the body x-axis to the relative velocity vector of the vehicle, positive rotation about the body z-axis frame by the right-hand screw convention.

Definition 2.4. (Rudder angle δ). The angle is the control input. The rudder angle operates between -0.39 to 0.39 rad. The range for the rudder (which is the difference between the maximum and minimum values) is 0.78 rad[39].

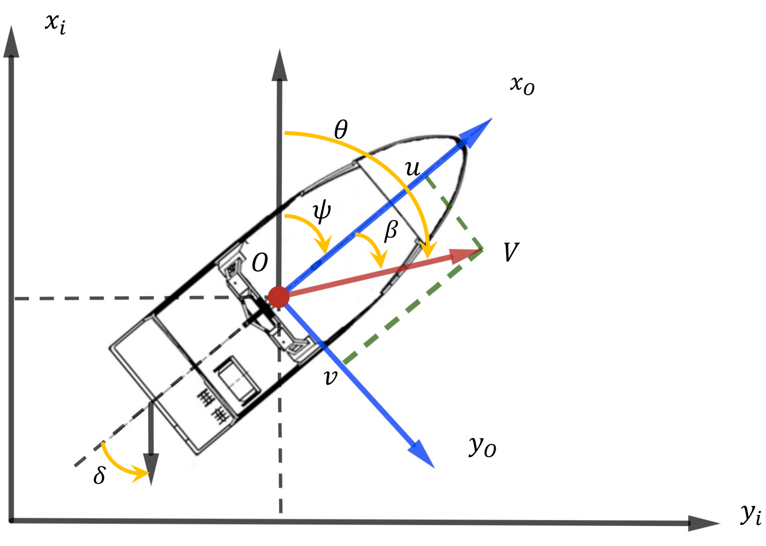

Figure 1. Schematic description of course, heading and sideslip angles

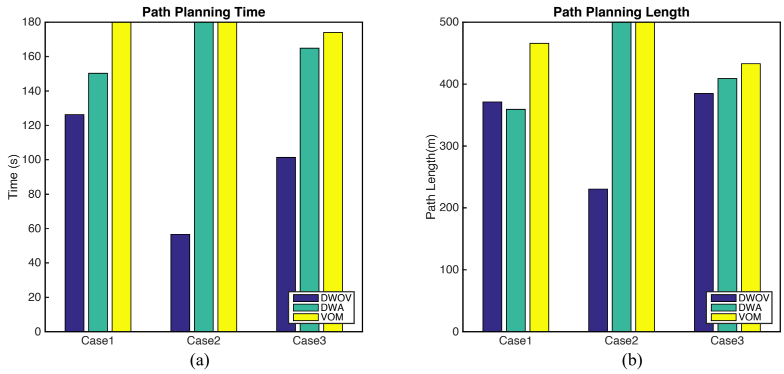

Figure 14. Three algorithms in optimal collision avoidance trajectory performance. (**a**) Total time. (**b**) Total collision avoidance trajectory length.

5. Conclusions

In this paper, DWOV, a new collision avoidance algorithm, is proposed. DWOV generated obstacle-avoidable path candidates. Path candidates were generated using the optimal collision avoidance point based on predictions of static and dynamic obstacles. Kinematics and dynamics constraints were taken into account in DWOV. The paper used simulations and experiments, demonstrating the proposed method to be effective. Through simulation experiments, the algorithm is more suitable for avoiding obstacles moving at a speed ratio of less than 1 to USV. The results of this study are limited to situations based on ship encounters in calm water conditions considered in this study. Additionally, no consideration was made of hull-to-hull interaction and hull-propeller-rudder-engine interaction between the two vessels, which is a direction for future research.

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Abbreviations

The following abbreviations are used in this manuscript:

DWOV	Dynamic windows velocity obstacle algorithm
DWA	Dynamic windows approach
VOM	velocity obstacle method
CPA	Closest Point of Approach
USV	Unmanned Surface Vehicle
NED	North-East-Down

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