ISBN: 978-981-18-5852-9
WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications
doi: 10.18178/wcse.2022.04.066

Dynamic Obstacle Avoidance for Unmanned Underwater Vehicles based on Velocity Obstacle

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Abstract. To address the problem of poor path planning and obstacle avoidance when the unmanned underwater vehicle (UUV) encounters dynamic obstacles such as floating objects, swimming fish, and ships during navigation in dynamic environments, a path planning method based on the velocity obstacle method is proposed. The desired speed is selected according to the position of UUV and the target, and the relative speed of UUV and the obstacle is calculated according to their ground speed, and the angular relationship between the relative positions of these two is used to derive a feasible path range for collision avoidance, and the feasible obstacle avoidance speed close to desired speed is selected to complete the avoidance of dynamic obstacles. The simulation results show that this method can make the UUV avoid obstacles in real-time in a complex environment with static obstacles and dynamic obstacles.

Keywords: unmanned underwater vehicle, velocity obstacles, dynamic collision avoidance

1. Introduction

As a lightweight underwater exploration tool, UUV has gradually become important equipment for marine resource exploration and strengthening national naval strength because of its small size, flexible operation, and high intelligent performance. In the complex and changeable ocean environment, the obstacle avoidance technology of UUV is the guarantee of its safe navigation and effective work. With the deepening of Marine exploration in various countries, how to further improve the ability of UUV in dynamic obstacle avoidance and path planning in complex ocean environments has become the key to restricting the effectiveness of UUVs [1]. Moreover, UUVs can overcome remotely operated vehicles (ROVs) to accomplish tasks that require human intervention. The limited communication range underwater requires UUVs to be independent of continuous manual control, and in many cases, requires fully autonomous operation of the underwater machine [2]. The use of unmanned underwater robots seems to be the main way in long-duration or deep missions [3], where UUVs can be used to accomplish practical tasks such as underwater scientific investigations, ocean sampling, and mine detection [4].

UUV obstacle avoidance planning methods usually refer to traditional mobile robot path planning methods, which are mainly divided into two categories [5]. One is the global path planning methods that rely on known environmental information, such as genetic algorithm [6], A* algorithm [7], ant colony algorithm [8], and neural network [9], etc. Although these methods can achieve good planning results, they ignore the unknown obstacles in the environment to the robot. The other category is the local path planning methods that rely on the perception of the surrounding environment, such as the artificial potential field method [10], velocity obstacle method [11], and dynamic window method [12], etc. The main drawback of these methods is the lack of global information, resulting in the planned path is often not the global optimum (such as the shortest path, minimum energy consumption), and in serious cases, the target is unreachable. Reference [13] combined the velocity obstacle method with the International Regulations for Preventing Collisions at Sea (COLREGS) to establish the optimal collision avoidance speed search rules based on the maritime crossing, overtaking, and head-on situations. Reference [14] combined the rolling window method with the velocity obstacle method, and designed a suitable 3D model predictive controller based on the rolling window method under the hybrid obstacle avoidance structure, and achieved stable tracking of the reference path by optimizing the objective function. The 3D velocity obstacle cone model was constructed while the window was rolling, and the critical collision point was calculated if the trigger collision avoidance condition was satisfied. The AUV was guided to safely avoid the obstacle by tracking the critical collision point. The dynamic obstacle avoidance planning of UUV can be based on this idea, in which the acquisition of a global reference path has been studied many times. The focus of this paper will be how to achieve collision-free between UUVs and effectively avoid unknown obstacles.

The velocity obstacle (VO) method was proposed by Fiorini [15], which is easy to understand and operate. VO has been well used in robot autonomous obstacle avoidance research [16]. In this paper, the velocity obstacle method derived from robot collision avoidance is used to consider time-varying obstacle avoidance in fixed path planning. By pre-setting the desired speed to reach the target point, the UUV forward-looking sonar is used to obtain the obstacle position, velocity information to provide accurate obstacle avoidance decisions. Finally, the angle between the UUV and the obstacle is calculated to get the speed obstacle region to obtain the feasible speed. The optimal avoidance speed was found among the feasible speeds to implement the avoidance. The simulation results verify the effectiveness of the algorithm.

2. Modeling

UUV has the characteristics of small size, fast speed, etc. In the unknown underwater dynamic environment, the forward-looking two-dimensional imaging sonar and underwater positioning system carried by itself can detect the size of the surrounding obstacles, relative position information, and the absolute position information of UUVs. The relative position information of the obstacles is converted to the ground coordinate system through the hull coordinate system so that the absolute position information of the obstacles can be obtained in the process of navigation and collision avoidance. UUV can obtain environmental information through the detection radar, and store the target position and speed that hinder normal and safe navigation of UUV. In this paper, we set that the UUV can obtain its position $P_u\left(x,y\right)$ through the positioning sensor device during navigation, and the speed of UUV is $v_u\left(v_x,v_y\right)$. To simplify its motion process, the state information of the UUV in the motion space is

$$\dot{X}=f(X,V) \tag{1}$$

Where $\dot{X}$ is the instantaneous change of the horizontal and vertical coordinates when UUV is moving, X is the current position coordinate of the UUV, and V is the current velocity of UUV.

When UUV collects the position and velocity information of the obstacle, and the UUV is expanded to a circle with a radius R_u according to the actual size, and the obstacle has a radius R_o, velocity $v_o\left(v_x,v_y\right)$. And taking UUV as a particle, the radius of the dynamic obstacle is expanded $R=R_u+R_o$. When UUV performs obstacle avoidance, then the relative velocity between its corresponding obstacles can be obtained $v_{uo}=v_u-v_o$, and the UUV velocity is expressed as v_{uo}, and the dynamic obstacle avoidance problem can be transformed into a static obstacle avoidance problem. The velocity obstacle method defines a relative velocity obstacle region, and when the relative velocity falls into this obstacle region, it is considered that a collision will occur between the two in the bounded time. Figure 1 shows UUV and obstacle modeling.

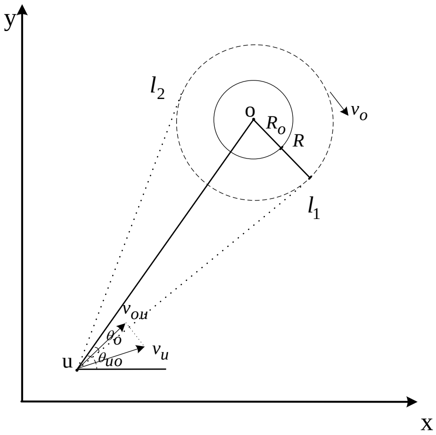

Fig. 1: Environment modeling

3. Velocity obstacle method

The Velocity Obstacle can be defined as follows:

$$VO_B^A\left(v_B\right)=\left\{v_A\left|\lambda\left(P_A,V_{AB}\right)\cap B\oplus -A\neq\varnothing\right.\right\} \tag{2}$$

where $\lambda\left(P_A,V_{AB}\right)$ denotes a ray with P_A as the vertex and V_{AB} as the direction. Let $A\oplus B$ denote the Minkowski sum of two objects A and B. Then, A and B will collide at some point when $v_A\in VO_B^A\left(v_B\right)$ (see Figure 2). Let the set of UUV reachable velocities at time interval Δt be

$$RV\left(t+\Delta t\right)=\left\{v\left|v=f\left(x,u\right),u\in U\right.\right\} \tag{3}$$

where *u* is the UUV controllable velocity and *U* is the set velocity to be controlled, and $v=f\left(x,u\right)$ is the UUV kinematic equation. Then it is necessary to find the velocity that satisfies

$$RAV(t+\Delta t)=RV(t+\Delta t)\ominus VO(t) \tag{4}$$

to avoid the obstacle.

At the moment *t*, UUV is at a position P_u and needs to reach the target position P_t, P_o is the position of the obstacle in the UUV detection environment, and assuming that the information is obtained by the sensor carried by the UUV itself, the distance *d* between the UUV and the center of the obstacle can be obtained. Before that, to make the UUV reach the target point, an ideal velocity should be set as follow:

$$v_d=\frac{v_{\max}\bullet\left(P_t-P_u\right)}{\left\|P_t-P_u\right\|} \tag{5}$$

Lead multiple lines from position P_u tangent to the obstacle after the expansion process to get two tangent lines l_1, l_1. Calculate the angle

$$\theta_{uo}=\arctan\frac{y_o-y_u}{x_o-x_u} \tag{6}$$

of the obstacle relative to the horizontal axis of the UUV coordinate system, and calculate the angle $\theta_o=\arcsin\frac{R}{d}$ between the tangent line and the line segment UO connecting the UUV and the obstacle. Then the UUV will collide with the obstacle when the velocity $v_{uo}=v_u-v_o$ of the UUV relative to the obstacle is at an angle $\theta\in\left(\theta_{uo}-\theta_o,\theta_{uo}+\theta_o\right)$ to the axis. Finally, the optimal velocity $v=\min\left\|v_d-v_u\right\|$ is selected from the feasible velocities so that the UUV can reach the target location in the shortest time while avoiding the obstacle.

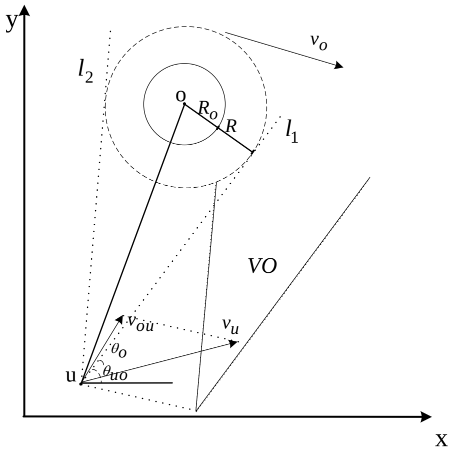

Fig. 2: The velocity obstacle of UUV

When two UUVs with similar collision avoidance meet, the basic VO method will lead to concussive obstacle avoidance, and the safe obstacle avoidance decision cannot be made. For this purpose, the RVO method of reference [17] is used to solve this problem. Instead of choosing a new speed for each UUV, the new speed it selects is an average of the current speed and the VO beyond it. Reciprocal Velocity Obstacle is defined as follows:

$$RVO_o^u\left(\mathbf{v}_o,\mathbf{v}_u\right)=\left\{\mathbf{v}_u'|2\mathbf{v}_u'-\mathbf{v}_u\in VO_o^u\left(\mathbf{v}_o\right)\right\} \tag{7}$$

Where $RVO_o^u(\mathbf{v}_o,\mathbf{v}_u)$ is the velocity set of UUV, where the speed is the average of the current speed and a velocity inside the VO. Its geometry can be understood as moving the velocity obstacle set VO vertex to $\frac{v_u+v_o}{2}$, as shown in Figure 3.

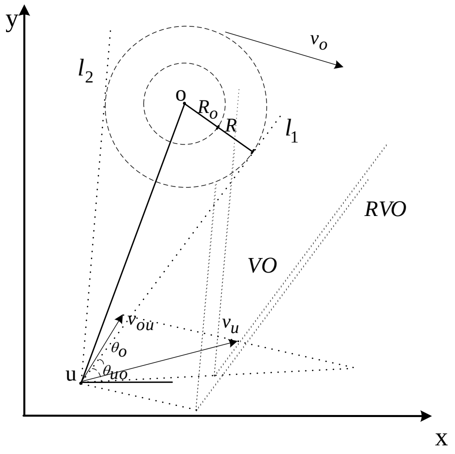

Fig. 3: The reciprocal velocity obstacle of UUV

Therefore, $RAV(t+\Delta t) = RV(t+\Delta t) \ominus RVO(t)$ need to be found to avoid the obstacles.

4. Simulation results and analysis

This section simulates the collision avoidance path in head-on scenario and the scenario when avoiding a multi-dynamic obstacle.

4.1. Head-on situation

UUV1 and UUV2 are generated at the positions $P_1(20,20)$ and $P_2(100,100)$ respectively, and their respective target points are the starting point of the other. They have obtained each other's position and speed information to simulate the path of avoidance when the two meet head-on. UUV uses the velocity obstacle method and considers its maneuvering motion characteristics for obstacle avoidance. Let the maximum speed of UUV be $V_{\max}=10\,m/s$. As shown in Figure 4, when *t*=10s, UUV1 and UUV2 slow down and prepare for obstacle avoidance. When *t*=12s, UUVs avoid each other from their respective right sides according to the velocity obstacle method, thus bypassing each other, and there is no danger of collision. When *t*=13s, UUVs start to resume their original course, and when *t*=20s, UUVs have safely reached their respective target points.

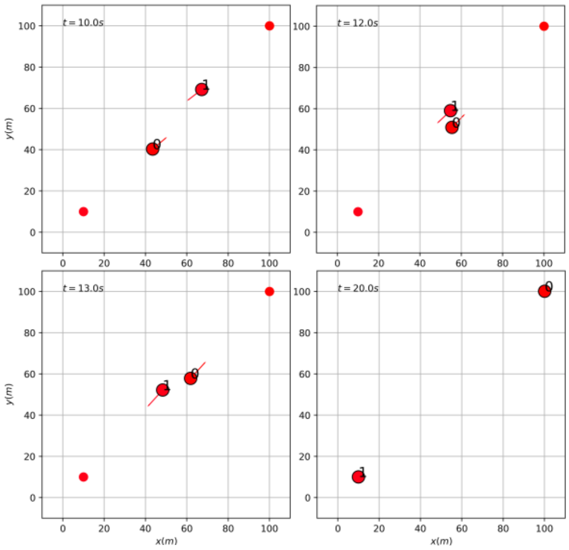

Fig. 4: Results of UUVs collision-free in a head-on situation

4.2. Multi-obstacles encounter situation

UUV1 and UUV2 are generated at the positions $P_1(0,20)$ and $P_2(20,0)$ respectively. They detect three obstacle ships are traveling with speed $v=6\,m/s$ to the lower right, their respective positions are $P_{o_1}(20,80)$, $P_{o_2}(15,90)$, $P_{o_3}(10,85)$. To verify the effectiveness of avoidance between UUVs, as well as for multi-dynamic obstacles. And the maximum speed of UUV is $V_{\max}=10\,m/s$. As shown in Figure 5, when *t*=7s, UUV1 and UUV2 slow down and are ready to avoid the multi-obstacle ships. When *t*=9s, UUVs slow down their speed to stay and wait for the obstacle ship to move beyond the UUV heading at a uniform speed, and then accelerates afterward to complete the obstacle avoidance safely. When *t*=11s, UUVs begin to resume their original route and move at a uniform speed. When *t*=20s, UUVs have all safely reached their respective target points.

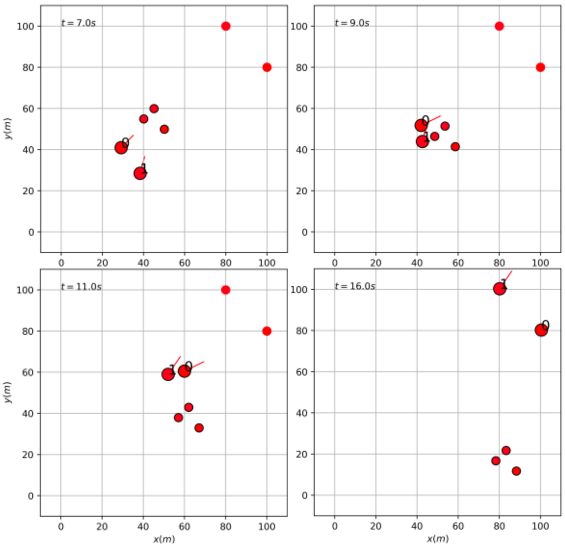

Fig. 5: Results of multi-dynamic avoidance for UUVs in an encounter situation

5. Conclusion

To improve the local dynamic obstacle avoidance capability of UUV, this paper establishes the speed obstacle area model of UUV and obstacles. This model was used to obtain the speed of the feasible interval for obstacle avoidance, and select the best ideal speed closest to the target from the feasible interval speed, which can get the nearest obstacle avoidance path. The advantage of this method is that it can make full use of the position and speed of dynamic obstacles to construct the shortest movement trajectory for safe navigation, ensuring that the UUV navigates on a trajectory close to the nearest one and improve the navigation efficiency of the UUV. At the same time, it can also enable UUV to have the ability of local dynamic obstacle avoidance to remove the threat of unknown obstacles in the complex underwater environment to the navigation safety of UUV and continue to navigate to the target point while completing obstacle avoidance. The effectiveness of the algorithm is verified through the corresponding simulation experiments.

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