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Ships Collision Avoidance Based on Quadrangle Ship Domain and Reciprocal Velocity Obstacle

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Abstract

Navigating the narrow and congested waters of the Yangtze River in China poses a significant challenge, leading to frequent ship-ship and ship-buoy collisions. In most cases of collisions between ships and buoys, the ship often hits and runs. This paper introduces a novel collision-avoidance decision method that employs the RVO (Reciprocal Velocity Obstacles) and QSD (Quantitative Ship Domain) to enable dynamic obstacle avoidance for ship-to-buoy and ship-to-ship, which complies with conventions on the international regulation for preventing collision at sea. QSD can dynamically adjust the ship domain model according to different speeds to address different encounter situations. The combination of RVO and QSD combines the dynamic ship domain with the obstacle avoidance algorithm, which makes the water transport safer than the traditional obstacle avoidance algorithm. In addition, this paper also compares the effects of VO (Velocity obstacle) and RVO, and the results indicate that RVO has smoother obstacle avoidance.

Keywords: Quantitative Spatial Domain, Reciprocal Velocity Obstacles, Collision Avoidance

1. Introduction

The Yangtze River in China features a meandering shape, which is considerably different from the planar shape of the ocean. The waterways in the Yangtze River are more heavily congested with ships compared with those in the ocean, increasing the possibility of collisions. The size of a buoy is much smaller than a boat or a bridge; therefore, a buoy can be easily ignored during ship navigation, leading to an increased possibility of accidents due to collisions. In such a case, it is difficult for the waterway management to identify the ship involved in the collision.

Khatib introduced a path plan method APF (artificial potential field) where a robot's motion is influenced by attractive forces towards targets and repulsive forces from obstacles to plan the route. APF is praised for smooth path planning but criticized for its susceptibility to local minima (Lazarowska, 2020), causing the robot to get stuck before reaching the goal. Originally designed for static environments (Selvam et al., 2021), APF requires significant computational adaptations for dynamic obstacle avoidance (Chen et al., 2020).

Huang, van Gelder and Wen present simulation results comparing VO (Velocity obstacle) algorithms with traditional methods in two encounter scenarios (Huang et al., 2018). VO algorithms are effective in avoiding collisions with non-linear and predictable target ships. However, the application of VO algorithms relies heavily on trajectory prediction, which may not always be accurate. Li and Zhang proposed a decision method based on the VO algorithm that addresses the limitations of the algorithm and improves collision avoidance in unmanned surface vehicles (Liu et al., 2022). Additionally, a convention on the international regulation for preventing collision at sea (COLREGs) is added to solve the limitations of the VO algorithm in emergencies (Kuwata et al., 2013). Berg, Ming and Manocha built upon the foundation of the VO to propose the Reciprocal Velocity Obstacles (RVO) model, which accounts for the interaction and mutual velocity obstacles between intelligent agents to achieve multi-agent path planning and avoidance (Xue et al., 2023). The RVO method is characterized by its bi-directionality, local perception, real-time operation, and simplicity (Kufoalor et al., 2018). As a commonly used local collision avoidance method, when combined with ship domains and navigational mark domains, the RVO effectively computes velocity obstacles for ships in dynamic environments, thereby calculating the way to prevent collisions and conflict solutions.

Fujii and Tanaka were the first to propose the concept of a ship domain, which is a closed area established in a plane space centered around a vessel under navigation (Liu et al., 2022). Goodwin introduced a ship domain composed of three unequal sectors, estimated through statistical methods to determine the ship domain (Liu et al., 2019). Ning Wang proposed an intelligent spatial collision risk assessment method based on the QSD (Quaternion Ship Domain) (Wang, 2010). Traditional ship domain models have limitations such as a lack of analytical description (Zhang and Meng, 2019), inability to accurately reflect the subjective intentions of ship handlers, and unsuitability for collision risk assessment and decision-making. To address these issues of traditional ship domains, the quaternion ship domain model was introduced. QSD describes the ship domain through four parameters (Silveira et al., 2022), offering a more intuitive and effective way for navigators to rapidly establish a feasible ship domain that can be used for avoidance decision-making.

Herein, the problem of ship-buoy collision is solved by employing QSD for ship domain and RVO for collision avoidance. Our approach prevents such collisions in advance with Obstacle avoidance strategy rather than assigning post-incident blame. Furthermore, it ensures navigational safety, reduces the workload associated with buoys, and extends the operational lifetime of buoys.

2. Related Work

2.1. Reciprocal Velocity Obstacles

The Figure 1 (a) show the geometrical define of Velocity Obstacle, the $A \oplus B$ denote the Minkowski sum of object A and object B , and the set $-A$ denote the reflection of set A , which is show in formula (1).

$$A \oplus B = \{a + b \mid a \in A, b \in B\}, -A = \{-a \mid a \in A\} \tag{1}$$

The definition of $VO_B^A(V_B)$ is show in formula (2), which represent that if $V_A \in VO_B^A(V_B)$, A and B will collide at some point in time.

$$VO_B^A(V_B) = \{V_A \mid P_A + (V_A - V_B)t \cap B \oplus -A \neq \emptyset\} \tag{2}$$

As depicted in Figure 1 (b), the apex of the RVO is located at the midpoint of the vector sum of the velocities of the two agents, which considers the motion of both agents. $RVO_B^A(V_B, V_A)$ is indicated by the formula (3), the V_A' is the new velocities chosen by agent A that lie outside the RVO area of agent B.

$$RVO_B^A(V_B, V_A) = \left\{V_A' \mid 2V_A' - V_A \in VO_B^A(V_B)\right\} \tag{3}$$

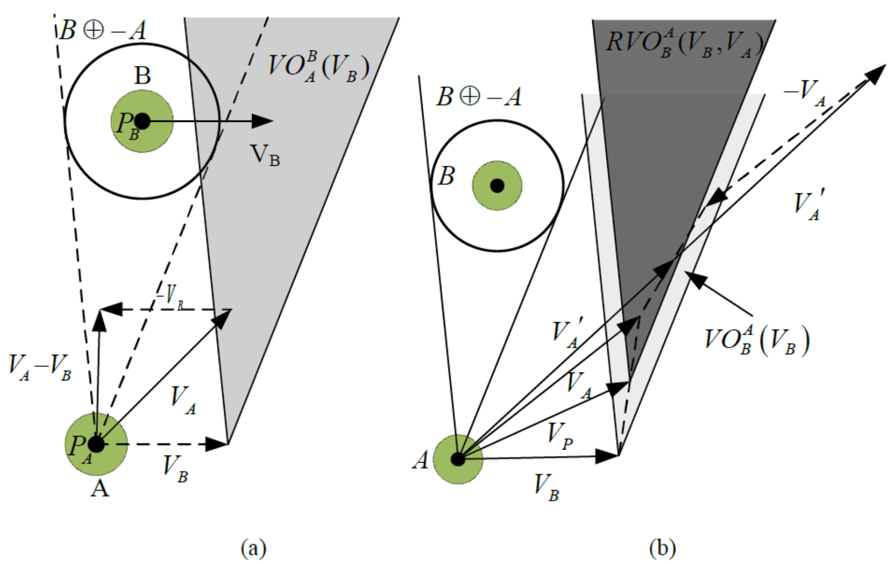


Figure 1: Principle of the VO algorithm and Generalized Reciprocal Velocity Obstacle.

3. Methodology

3.1. Buoy Domain Combined with RVO

Drift of buoys and potential errors in buoy data are considered. By increasing the radius of the boundary sphere, navigational safety is improved and the risk of collisions and accidents is minimized. The method is simple and practical and is an effective solution. The buoy domain is shown in Figure 2 (a). Since buoy targets are small and not as visible as ships, their buoy domain is defined as a circle twice the radius of the buoy. The buoy domain is applied to the RVO as shown in Figure 2 (b), where two tangent lines are drawn from the origin of the ship domain to the buoy domain in the geometric diagram thereby obtaining the RVO about the buoy.

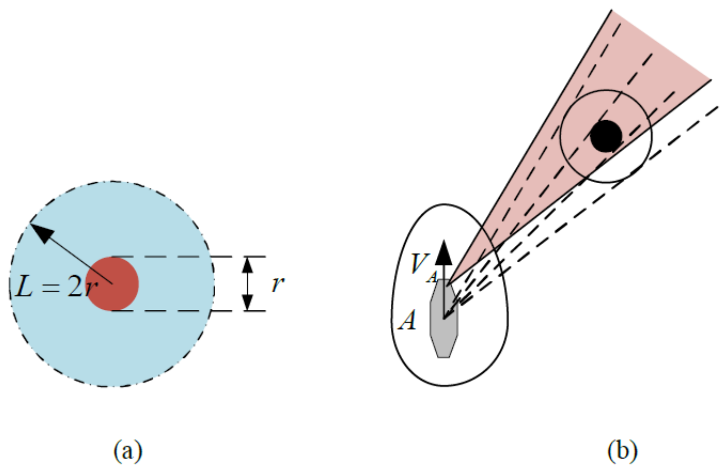


Figure 2: The domain of buoy and a buoy as obstacle for RVO.

3.2. Ship Domain Applied with RVO

QSD can dynamically adjust the shape of the ship domain according to the speed and encounter angle of the target ship. By combining the quaternion ship domain with the RVO algorithm, the timing and method of collision avoidance can be judged based on the risk of collision. This fusion method can address the situation where the target ship temporarily changes ships course and the capability for emergency collision avoidance.

Formula (4) is the contour line calculation formula for QSD. The value of k in the formula determines the shape of the QSD, as shown in the Figure 3. The larger the value of k, the closer the shape of the QSD is to a square or an ellipse with a smoother boundary. Whereas the smaller the k value, the closer the shape of the QSD is to a quadrilateral with a sharper boundary. Therefore, the k value can be used to adjust the shape of the QSD to suit different ship encounter situations.

$$f(x,y) = \left(\frac{2x}{(1+sgnx)R_{fore} - (1-sgnx)R_{aft}}\right)^k + \left(\frac{2y}{(1+sgny)R_{starb} - (1-sgny)R_{port}}\right)^k \quad (4)$$

In order to combine Ship Domains with RVO, the integration of bounding spheres with QSD is utilized. As Figure 4 shown in the diagram, a bounding sphere is constructed based on Ship B's QSD. Tangent lines are drawn from the center of Ship A's domain to the bounding sphere of Ship B's domain, which are represented by dashed lines in the figure. The diameter of the bounding sphere is determined by the sum of the longitudinal radii at the front and the rear of the ship. By shifting the center point of the ship domain upward by half the difference between the front and rear longitudinal radii, the bounding sphere can completely cover the QSD region.

The RVO algorithm is a method for navigation and dynamic obstacle avoidance in localized environments, and is particularly suitable for dealing with situations where the interaction between an individual and multiple surrounding targets or obstacles is complex. With the application of the RVO algorithm, ships can navigate more safely, effectively avoid collisions, and find suitable paths to reach their destinations in localized environments.

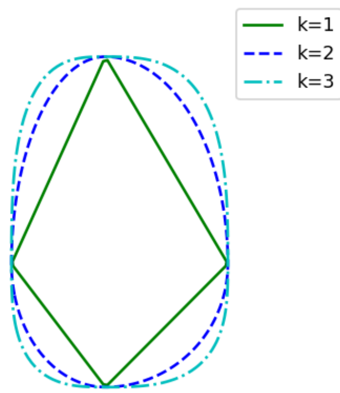


Figure 3: Quadrangle ship domain with different k = 1, 2, 3.

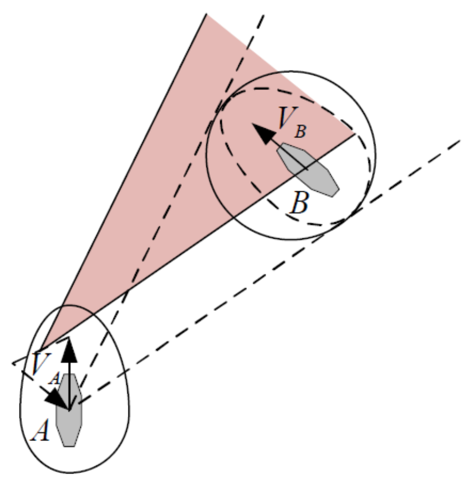


Figure 4: Appliance of bounding spheres with QSD for RVO.

4. Result and Analysis

When two intelligent agents A and B have velocities that lie within each other's VO, they will opt to change their velocities to avoid a collision. However, as each agent also chooses to change their velocity, may lead to a situation where both select the same velocity in the next cycle, thus entering into each other's VO once again. The RVO method assume other agents will make similar collision avoidance decisions. By computing an optimal velocity for each agent that is as close as possible to their preferred velocity while avoiding collisions with others, the RVO method enables safe and smooth navigation among agents, circumventing the occurrence of oscillation. As shown in Figure 5 (a) represents the obstacle avoidance process of VO and Figure 5 (b) represents the obstacle avoidance process of RVO, the obstacle avoidance strategies of two agents on a head-on collision course. The obstacle avoidance strategy of RVO is smoother than VO can be clearly seen from Figure 5.

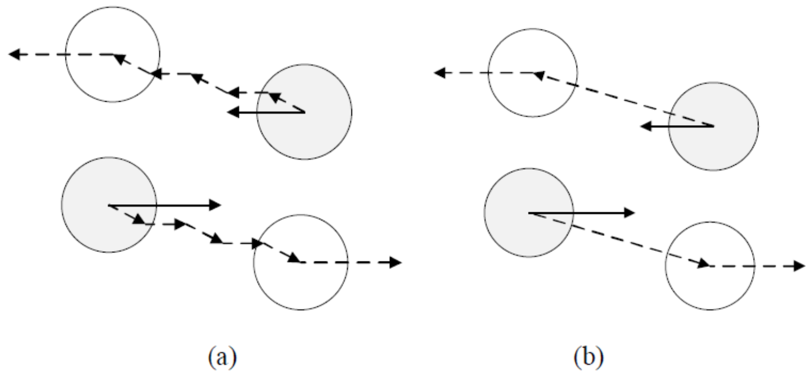


Figure 5: Collision Avoidance with VO and RVO.

RVO reduces the oscillation than VO, in combining the ship field with VO as shown in Figure 6 shows the obstacle avoidance effect of combining the ship field with VO, assuming four directions of the ship, ship 1 meets ship 2 head on, ship 3 and ship 4 meet head on, Figure 6 (a) shows that at the time of the four-ship meeting each ship has already made the direction adjustment according to COLREGs. Figure 6 (b) reveals that during the encounter of four ships, the speed adjustment ship 2 to avoid ship 3 exhibits noticeable oscillation.

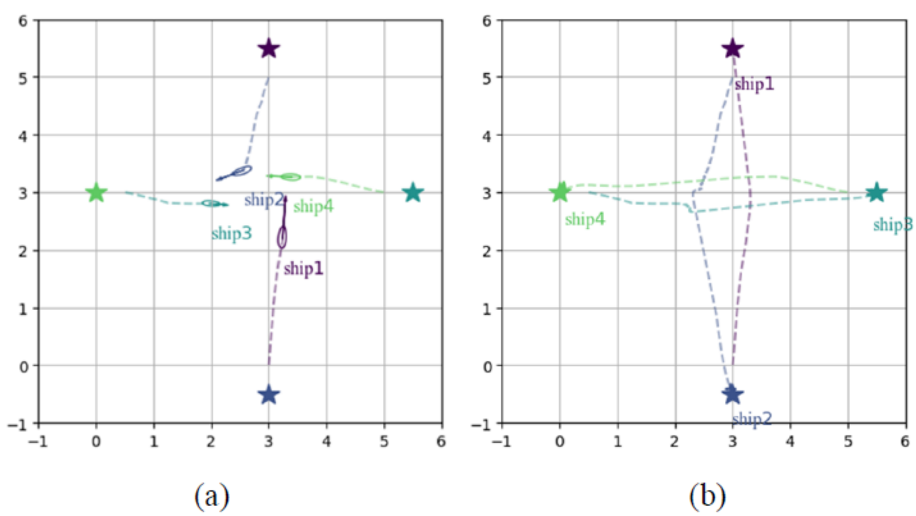
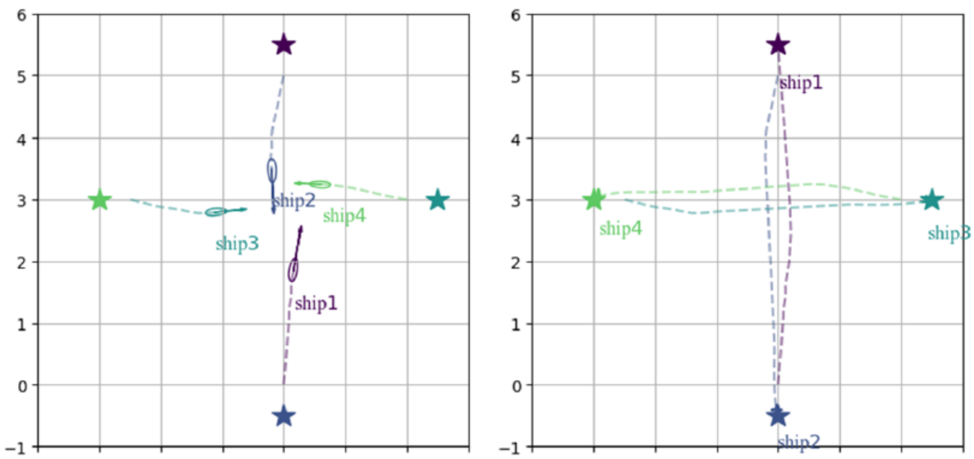


Figure 6: QSD-VO-based algorithm collision avoidance.

Figure 7 shows the simulation of collision avoidance by combining the ship domain with RVO as the above VO The ships start from four directions and meet two by two head-on, using RVO for obstacle avoidance. Comparing the speed adjustments in the two images, figure (a) demonstrates that ship 2, when avoiding ship 3, experiences less oscillation using RVO as opposed to VO. Furthermore, figure (b) shows that RVO yields a smoother navigation than VO during the whole process of obstacle avoidance.

The process of a ship avoiding a buoy is shown in Figure 8, where the circle represents the buoy and the ship is represented by a quaternion, and the ship always avoids the speed cone of the buoy and travels outside of its speed cone.



(a) (b)

Figure 7: QSD-RVO-based algorithm collision avoidance.

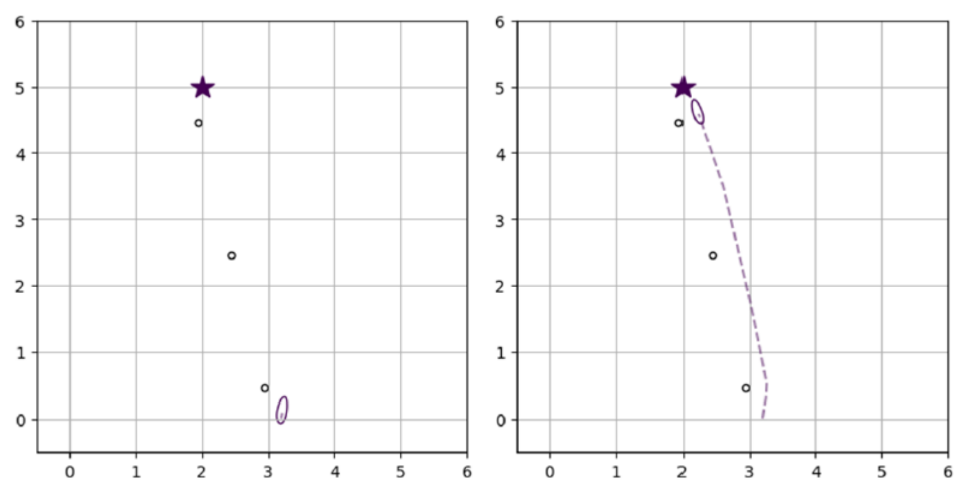
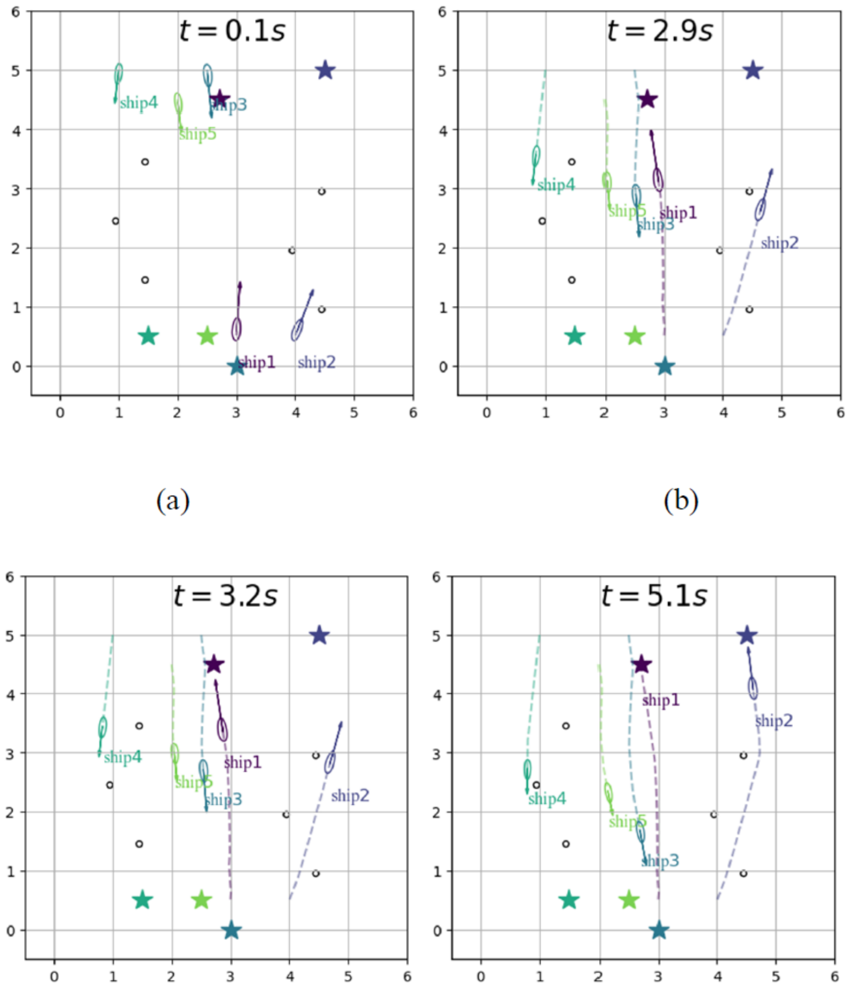


Figure 8: Ship-to-buoy collision avoidance.



(a) (b)

(c) (d)

Figure 9: Hybrid condition collision avoidance results.

Collision avoidance between ships and between ships and buoys in a complex navigational environment is a task that requires a high degree of precision and real-time response. As shown in Figure 9, this process is demonstrated by simulating a real navigational situation to show how a ship dynamically adjusts course and speed to comply with the collision avoidance rules and ensure safe navigation. In the simulation, both Ship 1 and Ship 3 execute the collision avoidance rule in the event of an encounter, they both yaw to the right as a way to avoid each other's course. A yaw to the right was executed to avoid a potential head-on collision, consistent with the COLREGs that advises ships to pass starboard to starboard in a meeting situation. At the same time, Ship 5 took the necessary safety measures when following Ship 3 after the encounter. Ship 5 maintained a safe distance by gradually slowing down to prevent a rear-end collision. On the other hand, Ship 2 and Ship 4 also demonstrated avoidance behaviors when ships approached the area of the buoy. The buoys, as fixed navigation points, are treated here as static obstacles. Ships need to recognize the position of the buoys in advance and take action to ensure that they do not enter the collision avoidance domains set of buoys.

5. Conclusions

In this paper, both QSD and RVO approaches are combined to simulate collision avoidance for ship to buoy and ship to ship, and COLREGs are taken into account. The size of the QSD model is dynamically adjusted according to different speeds to ensure safety under various navigational conditions. The combination of the QSD model and the RVO algorithm further enhances the efficiency and safety of collision avoidance for ships in complex waters, and provides a new perspective for the development of automatic navigation systems for ships.

In terms of dynamic obstacle avoidance applications for ship to buoy and ship to ship, the RVO algorithm can be used to dynamically adjust the heading according to the position and speed of the ship to avoid collision with the buoy or other ships. By updating the speed and direction of the ship in real time, RVO is able to coordinate between ships to avoid collisions and avoid obstacles efficiently and effectively.

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