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Autonomous collision avoidance for complex multi-ship encounters based on improved dynamic window approach

Xiaoru Ma[1], Hongguang Lyu[1,2,*], Guifu Tan[1], Xikai Kang[1], Yong Yin[1,2] and Tongtong Guo[3]

[1] Navigation College, Dalian Maritime University, Dalian 116026, China
[2] State Key Laboratory of Maritime Technology and Safety, Dalian Maritime University, Dalian 116026, China
[3] China Ship Scientific Research Center, Wuxi 214082, China

* Correspondence author; E-mail: lhg@dlmu.edu.cn.

Highlights:

- A hybrid risk assessment model combining VO and CPA/TCPA is constructed to accurately identify risk targets in complex encounter scenarios.
- A COLREGs-based responsibility allocation mechanism is integrated into the velocity space and evaluation function, explicitly constraining the search based on stand-on ship or give-way ship obligations, while also taking into account the collision risk among other vessels in the scenario.
- The IDWA evaluation function is redesigned with risk indices and compliance penalty terms, enabling autonomous, rule-compliant collision avoidance without inter-ship coordination.

Abstract: Achieving autonomous navigation requires Maritime Autonomous Surface Ships (MASS) to overcome difficulties in recognizing intricate multi-ship encounter situations and developing appropriate collision avoidance strategies. To address the above issues, this study first integrates the Velocity Obstacle (VO) with Closest Point of Approach/Time to Closest Point of Approach (CPA/TCPA) into the collision risk identification of ships. This enables the own ship (OS) to determine the risk posed by target ships (TSs) in the scenario. Secondly, the paper further discusses complex multi-ship encounter scenarios, based on 1972 International Regulations for Preventing Collision at Sea (COLREGs), it classifies responsibilities to determine the set of give-way ship and stand-on ship obligations. Finally, the derived responsibility set is incorporated into Dynamic Window Approach (DWA), allowing the enhanced Multi-Vessels Velocity Obstacle and Improved Dynamic Window Approach (MVO-IDWA) algorithm to automatically select optimal decisions in complex multi-ship encounter scenarios and ensure the ship reaches its destination safely. Centering on the challenge of avoiding collision decision in multi-ship complex encounter scenarios, this paper proposes the integration of ship responsibility sets with the MVO-IDWA algorithm. Analysis of the results establishes that the proposed algorithm can consider the inter-ship responsibilities, risk levels, and movement trends of TSs in multi-ship encounters, thereby realizing autonomous ship collision avoidance.

Keywords: multi-ship encounter situation; autonomous collision avoidance; velocity obstacle; dynamic window approach

1. Introduction

With the advancement of intelligent technologies in the global shipping sector, Maritime Autonomous Surface Ships (MASS) have become a research hotspot in the shipping field. The core of their autonomous navigation capability lies in safe and optimal avoiding collision decision-making. As a key link in MASS autonomous navigation, ship collision avoidance is directly related to maritime traffic safety and waterway navigation safety, and collision avoidance decision-making in complex encounter scenarios is an important challenge facing the industry.

At present, ship collision avoidance algorithms are gradually maturing. Domestic and international studies on decision-making for avoiding ship collision has forms a closed loop consisting of three links: collision risk identification, ship encounter situation judgment, and autonomous avoiding collision decision-making algorithms [1]. When there is a collision hazard of collision between each ship, the encounter situation can be divided and corresponding avoiding collision actions can be taken to eliminate the collision risk in accordance with the theoretical provisions of the International Regulations for Preventing Collisions at Sea (COLREGs).

When multiple ships encounter varying degrees of collision risk during navigation, their complex multi-ship encounter situations are difficult to judge due to the characteristics of a large number of ships, complex dynamic interaction relationships, and intertwined constraints of COLREGs. There have been numerous studies in this field. Zhao *et al.* [2] proposed a ship collision early warning model derived from fuzzy logic. The model quantifies collision risks through a fuzzy inference system and constructs a graphical risk assessment framework covering 48 meeting scenarios in combination with the COLREGs. Cho *et al.* [3] systematically integrated the COLREGs and adopted a symmetric role classification method to resolve role conflicts among multiple ships, ensuring the consistency of collision avoidance instructions. Song *et al.* [4] established a supervised learning-based support vector machine framework. This model learns from the collected multi-ship encounter situations and can be used to predict ship behaviors under different encounter scenarios. Tong *et al.* [5] identified influential ships by improving the WVoteRank algorithm, and constructed a complex network by combining ship distances and collision risks to help Ship Traffic Service (VTS) focus on high-risk areas. Gao *et al.* [6] proposed a multi-ship avoiding collision model based on the Attention-Enhanced Graph Convolutional Network for Spatiotemporal Boundary and Node Analysis. This model learns the decision-making process for avoiding collision experience of human navigators through AIS big data. Lyu *et al.* [7] proposed a method for complex multi-ship encounter situations based on risk quantification, COLREGs constraints, and cluster analysis of the Velocity Obstacle (VO) algorithm. Sui *et al.* [8] abstracted ship encounter scenarios as a linear dynamic system to deepen the understanding of situations. Integrating complexity indicators and risk indicators, he proposed a COLREGs-based maritime traffic advisory framework. Zhang *et al.* [9] continuously monitors and analyzes the behavior of give-way ships, and adopts the Dempster-Shafer theory to evaluate their cooperative intentions, thereby reasonably determining the optimal action timing for stand-on ships in multi-ship encounter scenarios.

Algorithms for avoiding collision decisions must be formulated through the identifying risks associated with ship collision and the categorization of multi-ship encounter situations. Such development is highly challenging and currently represents a research hotspot within the maritime engineering field, such as the VO algorithm, Artificial Potential Field (APF), and Dynamic Window Approach (DWA). The VO principle involves converting dynamic collision problems into static ones: by superimposing the position information and speed vectors between the robot and obstacles, a collision risk region is formed. The robot's movements must stay outside this obstacle region to prevent collisions [10]. Huang *et al.* [11] reviewed diverse VO algorithms, including Non-Linear VO (NLVO), Linear-VO (LVO), and Probabilistic Linear-VO (PLVO) algorithms, which support maritime collision avoidance decision-making. He pointed out that VO algorithms rely on trajectory prediction, but the prediction accuracy is not always guaranteed, and they cannot yield optimal decision-making solutions. Huang *et al.* [12] presented a Generalized VO technique which incorporates ship dynamics, taking into account distance discrepancies arising from the movement of other ships. Zheng *et al.* [13] also integrates VO with COLREGs, Closest Point of Approach (CPA), and Time to Closest Point of Approach (TCPA) for ship collision avoidance. However, that work focuses primarily on two-ship pairwise encounters and employs a single-layer risk threshold without embedding an explicit responsibility allocation mechanism into the velocity feasible interval. Currently, VO algorithms cannot get the optimal decision within the speed interval. While VO determines a safe velocity interval, it doesn't account for the limitations of the ship's motion performance in selecting the velocity vector. In the autonomous avoiding collision field, the method basic principle of APF involves creating an artificial potential field around both the ship and obstacles, ship is attracted towards its goal and repelled by obstacles, guiding it along a safe path while avoiding collisions. Lyu *et al.* [14] presents a real-time and deterministic path planning algorithm for autonomous ships, utilizing a modified APF algorithm that integrates COLREGs-compliant avoiding collision strategies for handling dynamic and static obstacles in complex maritime environments. Although the current APF algorithm integrates COLREGs requirements and TS behavior modeling, it still faces the problems of computational complexity and local optimality when dealing with multi-ship scenarios and complex environments, and fails to take into account the behavioral interactions among other ships.

The DWA was initially introduced by Fox *et al.* [15], optimizes velocity vectors by strictly adhering to kinematic and geometric constraints. Due to its effectiveness in local trajectory planning, it has been widely adapted from robotics to MASS. Early adapted, such as Yao *et al.* [16] focused on performance metrics, integrating the energy consumption models and fuzzy logic to enhance the evaluation function in DWA. However, unlike general robotics, maritime navigation requires strict adherence to COLREGs. Consequently, recent research has focused on integrating COLREGs into the DWA. Sun *et al.* [17] addressed this by presenting a control algorithm for real-time collision avoidance, adding a rudder angle term and a danger function aligned with COLREGs. Similarly, Guan *et al.* [18] proposed a hybrid approach fusing the A-star algorithm with the DWA in consideration of COLREGs. Despite these advancements in static compliance, effective collision avoidance against dynamic obstacles remains a critical challenge. To mitigate this, hybrid approaches combining DWA with VO algorithms have emerged. Wang *et al.* [19] integrating the VO algorithm into the DWA to reduce MASS's exposure to dynamic obstacles, but failed to take into account the constraints of the COLREGs. Other hybrid frameworks have addressed specific navigation challenges: Xu *et al.* [20] adopted the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm and an enhanced A* algorithm to search for a global path compliant with COLREGs. Subsequently, culminating in the application of the DWA algorithm to handle local collision risk assessment based on AIS data. Li *et al.* [21] proposed fusing the APF method with some ideas of the

DWA to solve the path oscillation problem. Currently, the DWA is primarily applied for avoiding static obstacles, with relatively few studies focusing on collision avoidance against dynamic obstacles. Consequently, current methodologies struggle to balance three critical aspects: dynamic collision avoidance, strict COLREGs compliance, and trajectory stability within uncoordinated, multi-ship environments. This limitation highlights the need for a unified framework that can accurately quantify risk and allocate responsibility in complex encounter situations. Recently, learning-based approaches, particularly deep reinforcement learning (DRL) [22,23] and Transformer-based multi-ship planners [24], have emerged as promising paradigms for collision avoidance, demonstrating strong adaptability in complex and dynamic encounter scenarios. However, such data-driven methods typically rely on large-scale training data and task-specific reward or loss designs, and their decision processes generally lack explicit responsibility reasoning, making it difficult to provide formal guarantees of COLREGs compliance. In this paper, we focus on the research of a rule-compliant and interpretable vessel collision avoidance framework, which explicitly embeds the responsibility allocation the COLREGs into the velocity-space decision-making process.

In summary, the main problems remaining in the present research on autonomous ship avoiding collision decision-making are as follows: (1) Current research on the classification of multi-ship encounter scenarios depends solely on the analysis of ship experience from historical AIS data, and there is a lack of consensus among ships in multi-ship encounter scenarios regarding such classification; (2) Existing methods for classifying multi-ship encounter scenarios without consideration of potential collision risks; (3) Collision avoidance algorithms for multi-ship encounter scenarios rarely account for the limitations of COLREGs, and most rely on mutual coordination among ships for collision avoidance without considering situations where coordination is not achieved.

To address the above problems, this paper proposes the Multi-Vessels Velocity Obstacle and Improved Dynamic Window Approach (MVO-IDWA) algorithm, which enables ships to comply with the requirements of COLREGs and autonomously take collision avoidance actions in complex multi-ship encounter scenarios without relying on inter-ship coordination. The main contributions of this paper are as follows:

(1) Risk Quantification: A hybrid risk assessment model combining VO and CPA/TCPA is constructed to accurately identify risk targets in complex encounter scenarios.

(2) Rule Embedding: A COLREGs-based responsibility allocation mechanism is integrated into the velocity space and evaluation function, explicitly constraining the search based on stand-on ship or give-way ship obligations.

(3) Optimization Function: The IDWA evaluation function is redesigned with risk indices and compliance penalty terms, enabling autonomous, rule-compliant collision avoidance without inter-ship coordination.

To address existing gaps in autonomous ship collision avoidance, this paper complies with the Rules and conducts targeted research: Chapter 1 applies the VO algorithm for collision hazard analysis and complex multi-ship encounter classification; Chapter 2 integrates responsibility into DWA to realize collision avoidance in complex scenarios; Chapter 3 verifies the proposed algorithm via simulations, aiming to solve uncoordinated collision avoidance challenges and validate the algorithm’s rationality.

2. Decision-making conditions in ship collision avoidance

2.1. Ship collision hazard

Navigators can compare the calculated CPA and TCPA between own ship (OS) and TSs with the corresponding safety thresholds. These thresholds vary across different navigation environments; this study is set in open waters, with a CPA threshold of 1 n mile and a TCPA threshold of 12 min. During navigation, navigators judge ship risks solely based on the CPA and TCPA between pairs of ships. However, in complex multi-ship encounter scenarios, a ship's behavior may affect the overall encounter situation and even extend risks to TSs involved. Therefore, this paper establishes a risk visualization method integrated with the VO algorithm.

The VO method offers an intuitive way to quantify the risk of ship collisions, which is more straightforward than TCPA and CPA. As indicated in Figure 1, the position of the target ship (TS) is represented by PT. To ensure that the OS can avoid collisions with TSs within a safe distance, an expansion circle is set. The radius of the expansion circle (PT) is equivalent to the set CPA value, which is 1 n mile. Starting from the OS's position PO, two rays are drawn that are tangent to the TS's expanded circle (Lam and Lan), forming a small conical region known as the TS's relative collision zone (RCC). By combining the ship's heading and speed with a given time, the corresponding velocity vector is simulated forward. In the Figure 1, the OS's velocity vector is represented by VO, OS's course represented by and the TS's velocity vector is represented by VT, TS's course represented by, BT represents the true bearing. Based on the VO and the VT, the relative velocity vector VR (VR = VO − VT) for the given time can be obtained, TS's relative course represented by. If the VR falls within the RCC, ships in encounter exist a danger of collision.

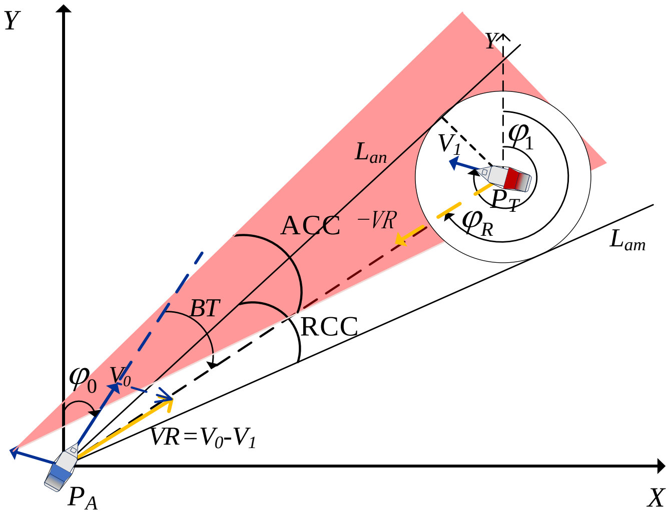


Figure 1. VO algorithm schematic.

However, the RCC is established in the relative velocity vector space, and in complex multi-ship encounter scenarios, there may be multiple relative velocity references, making it difficult for the OS to intuitively make an avoidance decision. To solve this issue, the Minkowski operation is applied. The RCC is then transferred along the heading of the TS from PO to the end of the VT vector, forming the absolute collision cone (ACC), which is shown as the red area in the Figure 1. The fundamental principle of the VO algorithm is to ensure that the OS's velocity vector (VO) endpoint fall without the RCC, as this would indicate a potential collision danger.

This paper, the VO is implemented for ship collision risk identification. The max speed of all ship in scenarios is set to 20 kn, and the max economic speed is 15 kn. Figure 2 illustrate the risk for multi-ship encounter scenarios. In the figure, the ship's Safe Velocity Cone (SVC) appears as a green semicircle with its radius determined by the maximum distance traversable in 5 minutes at top speed. Positioned at the bow is a thin line showing the velocity vector for the current speed over 5 minutes, while the stern displays a dotted line representing the 2-minute wake path, where data is logged every half minute. Different ships and their wakes are distinguished by different colors: OS is blue, TS1 and TS2 are red and purple respectively, as indicated in the legend at the bottom right corner. Starting at the OS, the RCC of the TS undergoes translation in the direction of the TS's velocity vector, moving to the vector's terminus according to the established vector length, thereby generating the corresponding ACC of the TS. If the endpoint of the OS's velocity vector falls within the ACC of the TS, a collision hazard exists between the OS and TS; if it falls without the ACC of the TS, there is no collision.

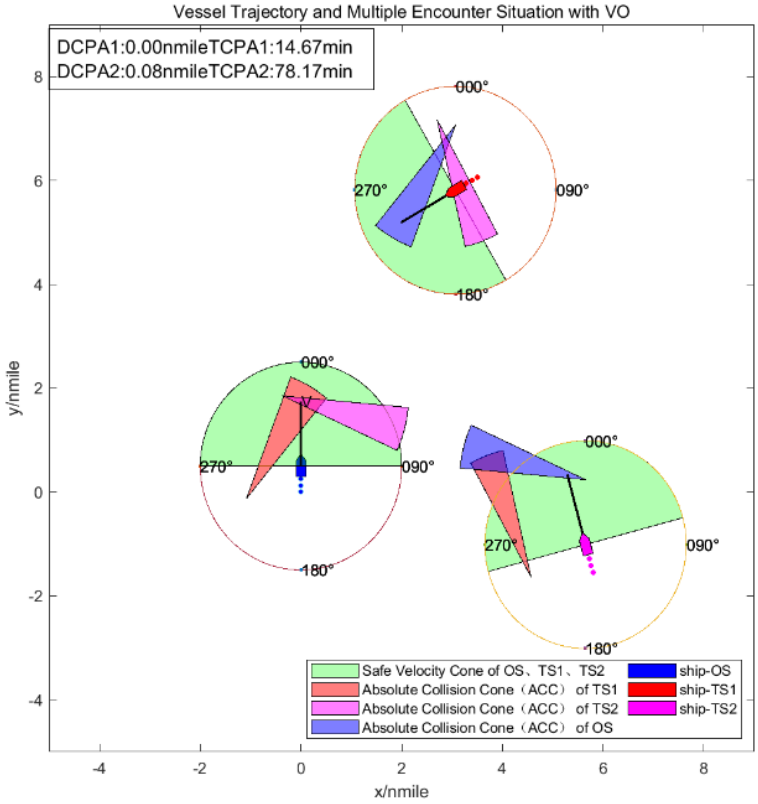


Figure 2. Collision hazard visualization using VO-based algorithms.

Utilizing this, it is possible to comprehensively consider the collision risks between each pair of ships, predict the potential collision avoidance actions that TSs may take, and track the latent collision risks with TSs during the development of the encounter situation.

2.2. Ship encounter situations and phases

Encounter stages and situations classification in the Rules mainly serves to constrain whether collision avoidance decision should be taken by ships in danger and what kind of actions should be adopted. Current research on avoiding ship collision algorithms focuses on when and what appropriate avoiding collision actions to take, *i.e.*, the timing of implementing the actions and the requirements for the actions taken.

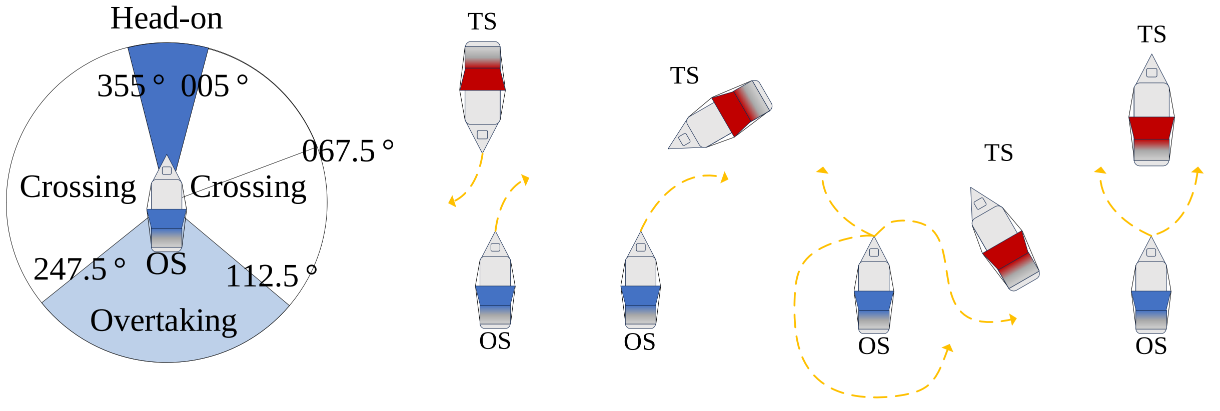
After determining the danger to the ship, regarding the classification of ship encounter situations and liability, the Rules divide the encounter situations between two ships into head-on, crossing, and overtaking situations. The liabilities of ships within an encounter situation are categorized as the give-way ship and the stand-on ship. Rule 8 and Rules 13 to 15 stipulate the collision avoidance actions for two-ship encounter situations and the responsible ships within such situations as follows:

Head-on situation: each ship shall take positive action to alter course to starboard as early as possible and pass from the port side of the other ship in the situation.

Crossing situation: if another ship is on the starboard side of the ship, the ship shall take avoiding collision action as early as possible, and such action shall avoid crossing ahead of the other ship's bow.

Overtaking situation: the ship shall take action to alter course substantially to port or starboard as early as possible. During the avoiding collision process, regardless of the change in the bearing between the ships, the ship shall not be relieved of its liability as the give-way ship to keep out of the way for the overtaken ship until it has finally passed and cleared the overtaken ship.

As summarized in Figure 3, this paper outlines the provisions of the Rules regarding ship liabilities and action requirements, listing respectively the encounter situations corresponding to different relative bearings of the TSs with respect to the OS during a two-ship encounter, as well as the collision avoidance measures that ships should take in different encounter situations. Within the encounter situations defined in the Rules, ship liabilities are categorized into the liability of the give-way ship and the stand-on ship. The collision avoidance actions corresponding to the give-way ship's liability are classified as follows: both ships alter course to starboard; the OS alters course to starboard; the OS reduces speed and alters course to starboard, or alters course to port to evade collision.



a) Head-on b) Small-angle c) Big-angle d) Overtaking

Figure 3. Schematic illustration showing the situation and OS's collision avoidance action.

As shown in Figure 4, when the TS poses a danger to the OS and is located at a relative bearing of 355 °to 112.5 °with respect to OS, the OS shall bear the liability of the give-way ship. If the TS is at a relative bearing of 292.5 °to 355 °and there is a hazard of collision with OS, it is necessary to consider the course difference between TS and OS to judge the encounter situation, and then determine the liability of OS. If the OS is overtaking TS, OS shall be the give-way ship; if it is a crossing situation, the OS shall be the stand-on ship.

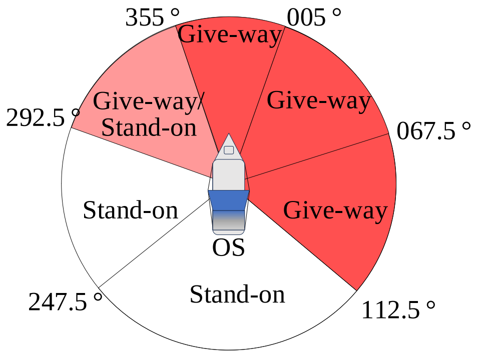


Figure 4. Responsibilities undertaken by OS in the situation schematic diagram.

As shown in Figure 5, the positive y-axis direction corresponds to the OS heading (000 °). Br demonstrates the relative bearing of TS to OS, and the direction of the TS's velocity relative to the OS is velocity direction symbol; the relative bearing of OS with respect to TS is denoted as Br1. When OS and TS exist a hazard of collision, if is satisfied, OS is in the situation of overtaking the TS; in other cases, TS and OS are in a crossing situation.

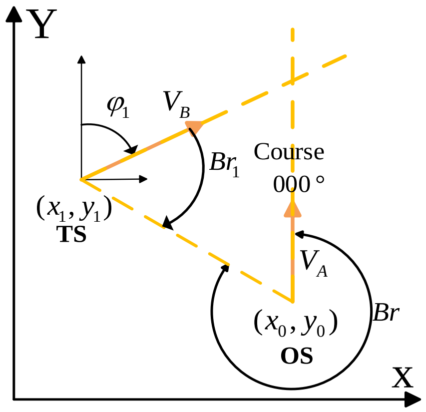


Figure 5. Relative motion parameter diagram.

When a ship sails in complex scenarios, it will encounter the following dangerous situations: such as being in danger with multiple other ships simultaneously; being in danger with one TS while another TS restricts the avoiding collision decisions of the OS; or when the OS needs to change course while sailing according to the original planned route, a new collision risk with TSs will arise. Therefore, during the ship's navigation, it is necessary to consider not only the risks between TSs and the OS, but also the risks among TSs, and whether they will have an impact on the normal navigation or collision avoidance actions of OS.

Therefore, this paper draws on the methods for identifying risks between TSs and dividing multi-ship encounter situations in existing literature, and advances the judgment from the similarities and differences of encounter situation to the similarities and differences of the responsibilities of OS, thereby simplifying the basis for determining the initiation of avoiding collision decision.

Taking the three-ship encounter scenario as an example, this paper first judges the risk conditions between each ship in the encounter scenario according to the risk judgment method proposed in the previous chapter. If a risk exists between OS and TSs, it then determines the type of encounter situation for OS with each of the TSs, and further identifies the responsibilities borne by OS, as well as whether a collision risk exists between the TSs.

Based on the similarities and differences in responsibilities, the scenarios can be divided into three categories:

(1) The OS is obligated to take decision as the give-way ship for all TSs;

(2) The OS is the give-way ship for one TS and the stand-on ship for the other TS;

(3) The OS is obligated to act as the stand-on ship for all TSs.

Obviously, the OS needs to consider when and what collision avoidance actions to take in Cases (1) and (2).

If OS is obligated to act as the give-way ship to all TSs, it is necessary to consider whether there is a collision hazard between the TSs. If no risk exists, the OS shall take into account the magnitude of the collision hazard, the distance, and the TCPA with each TS, giving priority to avoiding the ship with a higher collision risk, and the avoiding collision actions shall be designed to avoid all TSs in the encounter scenario in one go as far as possible. If a collision risk exists between the TSs, OS needs to consider the time sequence of actions to be taken by itself and TSs, judge whether the TSs have taken avoiding collision actions based on changes in the Collision Risk Index (CRI) value, and also assess whether the collision avoidance and subsequent resumption of navigation actions of TSs are contradictory to its own collision avoidance actions. If the TSs take collision avoidance actions earlier than OS, the OS shall leave sufficient room for the TSs to resume their navigation. If the TSs take such actions later, the OS shall take large-scale actions as soon as possible to leave enough time and space for the TSs to make their decisions.

If OS holds the responsibilities of being the stand-on ship and the give-way ship respectively to TSs in the scenario, it shall consider whether there is a collision hazard between the TSs. It is necessary to take into account the actions of the TS that is obligated to give way to OS and the nature of the responsibilities it bears. If there is no collision hazard between the TSs, OS shall take collision avoidance actions to keep clear of the TSs, and observe the responses of the give-way ship in the scenario to its own collision avoidance actions, making every effort to fully keep clear of the give-way ship in the scenario. If there is a collision risk between the TSs, OS shall consider the responsibilities among the TSs and whether there is coordinated collision avoidance between them, and shall keep a minimum safe distance to break away from the collision risk as far as possible, while leaving sufficient collision avoidance space for the TS with corresponding responsibilities in the scenario.

If OS acts as the stand-on ship to all TSs in the encounter situation, it shall maintain its course and speed during the encounter phase, but still needs to monitor whether there is a risk between the TSs and itself to ensure the safety of OS.

3. MVO-IDWA-based decision-making for avoiding ship collision

An autonomous multi-ship collision prevention algorithm combining VO with improved DWA, designated as MVO-IDWA, is introduced in this study. This approach retains traditional DWA's real-time computational benefits while resolving random steering tendencies in standard DWA and evaluation shortcomings in VO methods. Vessel information for OS and TS, including positional data, velocity, heading angle, and maximum acceleration rates (linear and angular), is processed to determine the dynamic window velocity feasible interval Vr for OS. Following this, trajectory simulation occurs over a predetermined forward time interval, with evaluation function G(v,w) scoring each projected path. The highest-scoring velocity instruction (v,w) is selected and applied continuously until reaching the designated waypoint.

The overall workflow of the proposed MVO-IDWA algorithm is presented in Algorithm 1, which describes the complete decision-making procedure from collision risk identification and multi-ship scenario classification to the computation of the velocity feasible interval Vr and the selection of the optimal velocity command (v,w).

Algorithm 1 MVO-IDWA for Autonomous Multi-ship Collision Avoidance

```
Input: OS state $P_A^t = [x, y, \varphi_0, V_1, w]'$ ;TS state {Position, Course, Velocity, Goal};
    // Collision Risk Identification
  If CPA_i < 1 nmile &&TCPA_i < 12 min   then
    Determine Encounter Situation (Head-on/ Crossing/ Overtaking) by relative bearing
        Res(i) = 0 (Stand-on ship) or Res(i) = 1 (Give-way ship).
  End if

    // Classify multi-ship scenario
        ensure two/three pairs of give-way and stand-on ship responsibilities
    // Commence collision avoidance maneuver
        $V_d = \{(v,w) | v \in [0, v_{\max}] \cap w \in [-w_{\max}, w_{\max}]\}$
        $V_m = \{(v,w) | v \in [V_{os} - V_a\Delta t, V_{os} + V_a\Delta t] \cap w \in [\omega_0 - \omega_a\Delta t, \omega_0 + \omega_a\Delta t]\}$
      For each TS_i, compute VO exclusion $V_{vo}(i)$ :
                $V_{vo}(i) = \{(v,w) | U(v,w) \cap ACC = \varnothing\}$    $Res(i) = 1$ (Give-way ship)
                $V_{vo}(i) = \{(v,w) | U(v,w) \subseteq (V_d \cap V_m)\}$    $Res(i) = 0$ (Stand-on ship)
        $Vr = V_d \cap V_m \cap V_{vo}(i)$

    For each (v,w) $\in$ Vr do
        $H(v,w)$ ← angular deviation of (v,w) toward goal
        $V(v,w)$ ← navigation speed value
        $D_{sum}(v,w)$ ← $D_{sum}(v,w) = D_1(v,w) + ... + D_i(v,w)$
        $Ris(v,w) \leftarrow \sum_{i=1}^{n} f(CRI_i, CPA_i, TCPA_i)$
        $Col(v,w)$ ← COLREGs compliance score based on $Res(i)$

          If Res (OS) = (1,1) and ∃TS with Res = (1,0):
            Score = f (pass_astern_all_TS)

            // Nested responsibility: OS must reserve maneuver space for give-way TS
          Else if Res(OS) = (1,0):
            Score = f (pass_astern_give-way_TS)

            // OS gives way to one TS, stand-on to another
          Else if Res(OS) = (0,0):
            Score = 0   // Maintain course and speed, full compliance score

        $G(v,w) = \alpha(\gamma_1 H(v,w) + \gamma_2 V(v,w) + \gamma_3 D(v,w) + \gamma_4 Ris(v,w) + \gamma_5 Col(v,w))$
     End for

     (v,w) ← arg max G(v,w) $\in$ Vr

     Repeat from line 1 until OS reaches Goal
```

The improvements of the MVO-IDWA algorithm proposed are reflected in the following three aspects: (1) The VO method is introduced into the velocity vector selection interval, and combined with the responsibility division, and the safe speed vector interval of the ship is screened out; (2) Risk evaluation and COLREGs evaluation are introduced into the evaluation function G(v,w), aiming to solve the problems that the collision avoidance measures obtained by the original DWA do not conform to the requirements for the encounter phases and the actions of give-way ships in encounter situations specified in the COLREGs, as well as the problem of excessive randomness in the decision of passing ahead of or astern of TSs; (3) The classification method for complex encounter situations proposed in the previous chapter is integrated into its evaluation function, so that the ship can still obtain the optimal collision avoidance decision when dealing with complex encounter situations.

3.1. Ship velocity feasible interval

In the process of selecting the speed feasible range Vr in the MVO-IDWA algorithm, the limitations of the ship's own motion capabilities and the restrictions of the unsafe zones set for dynamic obstacles are taken into account. Through this screening and constraint mechanism, the algorithm can effectively obtain a set of velocity vectors that not only conform to the ship's motion characteristics but also ensure navigation safety.

For the OS, the maximum economic speed at initial state is V_{os}, while V_a represents the maximum acceleration, ω_0 denotes the angular velocity, and ω_a indicates the angular acceleration, operating within time interval Δt. Maximum linear velocity and maximum steering angle interval are configured by the ship itself as V_d:

$$V_d = \{(v, w) | v \in [0, v_{\max}] \cap w \in [-w_{\max}, w_{\max}]\} \tag{1}$$

Based on the ship's kinematics and the limitations of the ship's own maximum acceleration and angular acceleration, for a specified time interval Δt, the velocity vector variation interval is obtained as V_m:

$$V_m = \{(v, w) | v \in [V_{os} - V_a\Delta t, V_{os} + V_a\Delta t] \cap w \in [\omega_0 - \omega_a\Delta t, \omega_0 + \omega_a\Delta t]\} \tag{2}$$

Considering the course and speed of the TS, the VO is used to detect ship risks. For the RCC of the relative speed vector between the OS and TS, the TS's ACC is obtained by moving along the TS's course by a distance corresponding to the TS's speed. Let U(v,w) denote the spatial occupancy set of the OS along its predicted trajectory under velocity vector (v,w) within a given prediction time horizon, *i.e.*, the set of positions that the OS may occupy in the future when traveling at (v,w). A velocity vector (v,w) is considered a feasible safe velocity V_{vo} if and only if U(v,w) does not intersect with the absolute collision cone (ACC) of the TS:

$$V_{vo} = \{(v, w) | U(v, w) \cap ACC = \varnothing\} \tag{3}$$

When OS is in a complex encounter situation, if ship responsibilities are not taken into account, the RCC of all TSs will be regarded as unreachable intervals for velocity vectors, leaving OS with few available actions. Therefore, Rules 16 and 17 are integrated into the selection of velocity vector intervals, and the responsibilities of the stand-on ship and the give-way ship are thus incorporated into the feasible velocity vector selection interval of OS. As mentioned in Rule 17, this rule does not relieve the give-way ship of its obligation to keep out of the way. Consequently, when OS is obligated to act as the give-way ship to all TSs in a complex encounter scenario, it shall maintain its course and speed in its maneuvering.

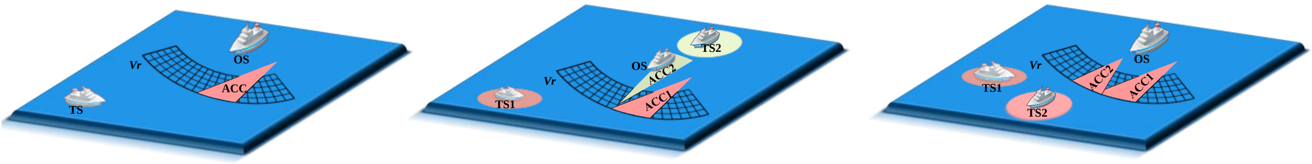
In all other cases, collision avoidance decisions must be taken. The setting of responsibility (*Res*) is as follows: *Res* is assigned a value of 1 if the ship is a give-way ship, and 0 if it is a stand-on ship.

The setting of responsibility (*Res*) is correlated with the decision-making of OS's feasible velocity vectors, with the provisions as follows:

$$V_{vo}(i)=\begin{cases}(v,w)\left|U(v,w)\cap ACC=\varnothing\right. & Res(i)=1\\(v,w)\left|U(v,w)\subseteq(V_d\cap V_m)\right. & Res(i)=0\end{cases}\tag{4}$$

where i denotes the number assigned to TS relative to OS in a complex multi-ship encounter scenario, with i = 1,…,n.

As shown in Figure 6, Figure 6a shows a collision risk between the two ships, where the TS is in a starboard crossing encounter situation with OS, and Vr represents the optional speed interval for the OS. Figure 6b depicts a three-ship encounter situation, TS1 is on the starboard side of the OS, forming a crossing situation with *Res*(*I*) = 1, while TS2 is overtaking the OS with *Res*(*2*) = 0. Thus, ACC1 is the red infeasible interval, and ACC2 is the green feasible interval for encounter phase. Figure 6c indicates that both TS1 and TS2 are at collision risk with the OS, with *Res*(*1*) and *Res*(*2*) both equal to 1. Therefore, both ACC1 and ACC2 are red speed infeasible intervals.



(a) (b) (c)

Figure 6. The speed feasible range Vr in the MVO-IDWA algorithm: **(a)** OS with Res = 1; **(b)** OS with *Res(1)* = 1, *Res(2)* = 0; **(c)** OS with *Res(1)* = 1, *Res(2)* = 1.

To ensure the ship's navigation safety, the speed feasible interval *Vr* is obtained:

$$Vr=V_d\cap V_m\cap V_{vo}(i)\tag{5}$$

3.2. Calculation of ship motion trajectory

When a ship is navigating, it is necessary to consider its own motion performance. Its motion coordinate systems are among which the ship's motion model in the horizontal plane is described by the inertial mathematical model O0−XYZ and the body-fixed coordinate system (both are right-handed rectangular coordinate systems).

The information of OS can be summarized as $P_A^t=[x,y,\varphi_0,V_1,w]'$, and when OS sails with a constant course and speed, *w*=0, with the speed variation set as $u=[v(i),w(i)]'$. The information of OS is summarized as $P_A^{(t+1)}=[x_{t+1},y_{t+1},\varphi_{t+1},V_{t+1},w_0]'$ at the next moment. In the velocity variation, the linear and angular velocities are designated by *v* and *w*, respectively.

$$P_A^{(t+1)} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \cdot P_A^t + \begin{bmatrix} \sin(P_A^t(3)) \times \Delta t & 0 \\ \cos(P_A^t(3)) \times \Delta t & 0 \\ 0 & \Delta t \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot u \tag{6}$$

3.3. Determination of optimal decision based on G(v,w)

The evaluation function within DWA operates on the speed feasible interval established in the preceding section to formulate secure and efficient strategies for avoiding ship collision, executing the top-rated speed-course decision set. While conventional DWA evaluation functions originate from target bearing, speed, and distance between ships *in situ*ation sub-functions, the G(*v*,*w*) evaluation function proposed herein incorporates both collision risk degree assessment and compliance evaluation sub-functions for ships:

$$G(v,w) = \alpha(\gamma_1 H(v,w) + \gamma_2 V(v,w) + \gamma_3 D(v,w) + \gamma_4 Ris(v,w) + \gamma_5 Col(v,w)) \tag{7}$$

In the formula, $\gamma_1, \gamma_2, \gamma_3, \gamma_4$ and γ_5 are the weights of each evaluation factor, and α denotes the normalization processing of its five elements.

(1) Target Heading Azimuth *H* (*v*,*w*)

The target heading function is calculated as shown in the formula, representing the angular difference between OS's viable course and the target point's bearing relative to OS, θ. The higher the evaluation score is when the bow of ship is directed toward the target point.

$$H(v,w) = 180^{\circ} - \theta \tag{8}$$

(2) Velocity *V*(*v*,*w*)

The velocity function is shown in Formula, which represents the ship's navigation speed value. Deceleration behavior can be incorporated when avoiding TSs. The ship's maximum economic speed is set as the maximum speed value, and the greater the deceleration, the lower the score.

$$V(v,w) = vt \tag{9}$$

(3) Distance Evaluation Between TS and OS *D*(*v*,*w*)

The distance function in the traditional DWA reflects the separation between the OS and static obstacles, with a higher score assigned for a greater distance. For ship-to-ship distance evaluation, a 2 n mile boundary threshold is implemented. Predictive simulation is conducted over a given time period interval using the previously obtained speed feasible interval range of the ship. The distance to TSs is saved at fixed time increments (set to 30 seconds), and the average distance during the simulation process is calculated. Average distances within the boundary threshold receive proportionally higher scores; those exceeding it are uniformly assigned a score of 1.

$$D_i(v,w) = \begin{cases} 0 & d_i \le 1 nmile \\ d_i - d_{safe} & 1 < d_i < 2 nmile \\ 1 & d_i \ge 2 nmile \end{cases} \tag{10}$$

In a complex multi-ship encounter scenario, it becomes essential to account for the separation between OS and each TSs. Therefore, the aforementioned distance evaluation functions for TSs need to be superposed, denoted as $D_{sum}(v,w)$:

$$D_{sum}(v,w) = D_1(v,w) + \ldots + D_i(v,w) \tag{11}$$

where i denotes the number of TS relative to the OS in the complex multi-vessel encounter scenario, with i = 1,…,n.

(4) Collision Hazard Evaluation Function $R\,(v,w)$

Ship collision hazard degree represents the hazard level between ships, with a value ranging from 0 to 1; The magnitude of the coefficient correlates positively with the degree of danger present between ships. As a result, an inverse relationship between risk magnitude and evaluation score is established within the ship risk evaluation function. Consequently, the correlation between the CRI and the collision risk evaluation function:

$$R(v,w) = 1 - CRI \tag{12}$$

$$CRI = W \cdot U \tag{13}$$

$$W = [w_{CPA}, w_{TCPA}], U = [u_{CPA}; u_{TCPA}]$$

$$u_{CPA} = \begin{cases} 0 & d_2 < |CPA| \\ \frac{1}{2} - \frac{1}{2}\sin\left[\frac{\pi}{d_2 - d_1}\left(|CPA| - \frac{d_1 + d_2}{2}\right)\right] & d_1 < |CPA| \le d_2 \\ 1 & d_2 < |CPA| \end{cases} \tag{14}$$

$$u_{TCPA} = \begin{cases} 0 & t_2 < |TCPA| \\ \left(\frac{t_2 - |TCPA|}{t_2 - t_1}\right)^2 & t_1 < |TCPA| \le t_2 \\ 1 & 0 \le |TCPA| \le t_1 \end{cases} \tag{15}$$

When a ship is in a multi-ship situation, it is essential to flexibly respond to the impact of the risk degree between two ships. Therefore, the aforementioned risk degree relationship between two ships needs to be considered in a superposed manner to derive the risk degree for multiple ships. It is required to calculate the sum of the risk values for the OS and each hazardous ship in the encounter scenario within the feasible velocity vector decision interval of the velocity vectors for the two ships:

$$Ris(v,w) = \sum_{i=1}^{n} R_i(v,w) = \sum_{I=1}^{n}(1 - CRI_i) = n - \sum_{i=1}^{n} CRI_i \tag{16}$$

where i denotes the number assigned to TS relative to OS in a complex encounter situation, with i = 1,…,n.

(5) COLREGs Compliance Evaluation $Col(v,w)$

Collision avoidance maneuvers for ships are regulated by COLREGs through defined responsibilities assigned to give-way and stand-on ships. In situations involving overtaking or crossing encounters where the TSs approaches from starboard, the OS is designated as the give-way ship. The preferred collision avoidance strategy mandates that the OS transits TS's astern, ensuring a CPA below −1 nautical mile:

$$Col_i(v,w)=\begin{cases}1 & CPA_i<-1nmile\\ 0 & CPA_i>1nmile\end{cases} \tag{17}$$

$$Col_{sum}(v,w)=Col_1(v,w)+\ldots+Col_i(v,w) \tag{18}$$

In multi-ship encounter scenarios, this paper takes the three-ship encounter scenario as an example, incorporates the three types of responsibilities mentioned in the previous chapter into the calculation of the *Col*(*v*,*w*), and needs to consider whether there is a risk between TSs, whether it is necessary to take TSs’ behaviors into account, and reserve maneuvering space for them. In this algorithm, the responsibility (*Res*) is defined as follows: *Res* is assigned a value of 1 for give-way ship and 0 for stand-on ship, and the responsibilities of ships in a scenario are corresponding to each other, *i.e.*, the number of ships with *Res* = 1 is equal to that of ships with *Res* = 0, and the total number of these two types of ships is at most equal to the number of ships in the scenario. Therefore, in the three-ship encounter scenario, this paper only discusses the assignment of give-way and stand-on ship responsibilities for two-ships scenario and three-ships scenario, as shown in Table 1.

Table 1. Responsibilities of each ship in complex encounter scenarios.

Ship Responsibilities in Complex Three-Ship Encounter Scenarios						
	Two pairs		Three pairs			
OS	1,1	1,0	1,1	1,0	1,0	0,0
TS1	0	0	1,0	0,0	0,1	1,1
TS2	0	1	0,0	1,1	1,0	1,0

When assigning two pairs of give-way and stand-on ship responsibilities, there are two scenarios: in both scenarios, the OS is at risk of collision with TSs, while no collision risk exists between TSs. The difference lies in two aspects: first, the OS assumes the responsibility of a give-way ship to both TSs, and its collision avoidance action should be designed to pass astern of TSs as far as possible; second, the OS undertakes the responsibilities of a stand-on ship to one TS and a give-way ship to the other, and its collision avoidance action only needs to comply with the requirements of the give-way ship responsibility and avoid creating a collision risk with the other ship.

When assigning three pairs of give-way and stand-on ship responsibilities, there are three scenarios; taking the OS as an example, collision risks exist between the OS and all TSs in the scenario, and according to the Res setting, the ship has three scoring combinations, which are defined as follows: (1,1) indicates that the OS is at risk of collision with all TSs and assumes the responsibility of a give-way ship to each of them; (1,0) indicates that the OS is at hazard of collision with all TSs and undertakes the dual responsibilities of a give-way ship to one TS and a stand-on ship to another, and (0,0) indicates that the OS is at hazard of collision with all TSs and assumes the responsibility of a stand-on ship to each of them. Among these combinations, if the (1,1) responsibility applies to a scenario with three pairs of give-way and stand-on ship responsibilities, it constitutes a responsibility-nested scenario, in which case the OS shall avoid collisions while reserving maneuvering space for the TS assigned with the (1,0) responsibility; for the (0,1) responsibility combination, there are two sub-scenarios, the first being that the OS acts as a responsibility-borne ship in a responsibility-nested scenario and thus shall avoid collision with the stand-on ship by maintaining the min safe distance as far as possible, and the second being that all ships in the scenario are assigned with the (1,0) responsibility and therefore the OS shall consider coordinating collision avoidance actions to keep clear of all TSs in the scenario simultaneously; for the (0,0) responsibility combination, the OS shall maintain its course and speed for navigation.

The priority determination in the three-pair responsibility scenario is instead determined adaptively through the following integrated mechanisms: at the velocity feasible interval screening stage, the ACC of each give-way TS is excluded as an infeasible velocity region, enforcing the fulfillment of give-way obligations as a prerequisite; at the evaluation function stage, the CRI dynamically weights the urgency of each TS's collision threat, guiding the OS to prioritize the most imminent danger via $Ris(v,w)$; the $Col(v,w)$ sub-function further scores each candidate velocity for COLREGs compliance, ensuring the final decision achieves optimality while satisfying all responsibility constraints simultaneously.

Although the COLREGs do not explicitly define the multi-ship encounter scenarios, this paper integrates the classifications of ship encounter situations, ship responsibilities, and the corresponding decisions to be taken by ships elaborated in Chapter 2 above into the $Col(v,w)$, so as to derive the optimal decision-making strategy for the OS in complex encounter scenarios.

4. Experimental validation

To verify the rationality of the simplified multi-ship encounter scenario proposed in this paper and the applicability of the proposed MVO-IDWA avoiding collision algorithm, four types of multi-ship encounter scenarios are designed for simulation experiments. Three pairs of give way and stand-on obligations apply to Case 1, Case 3 and Case 4, whereas only two pairs apply to Case 2. For the MVO-IDWA algorithm proposed in this paper, multiple experiments are conducted by setting different parameters, and the feasible parameters obtained are shown in Table 2.

Table 2. Simulation experiment parameters.

Main Parameters	**Value**
Weight of Heading Evaluation Function γ_1	0.1
Weight of Speed Evaluation Function γ_2	0.1
Weight of Distance Evaluation Function γ_3	0.2
Weight of Collision Risk Evaluation Function γ_4	0.5
Weight of Rule Evaluation Function γ_5	0.1

4.1. Case 1: three-ship encounter situation collision avoidance

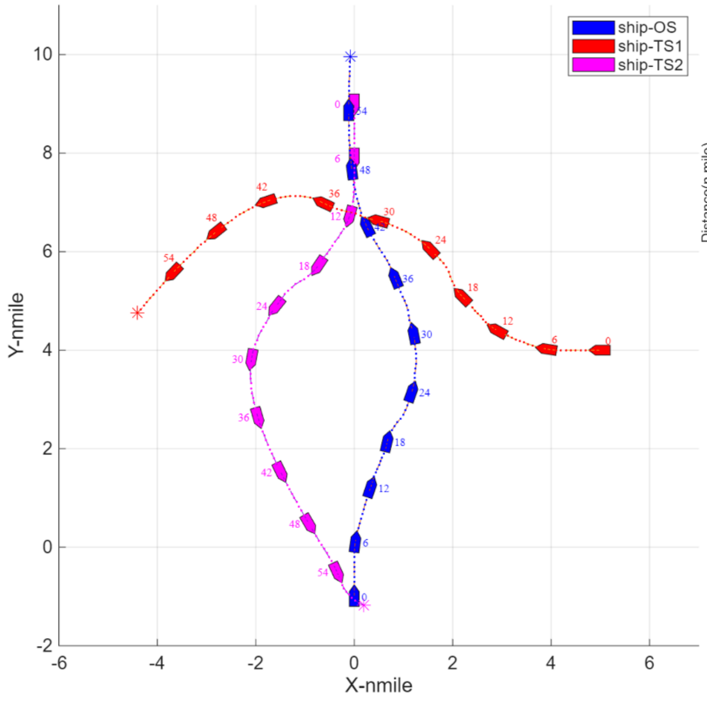
The original parameters of all ships in this experiment (Case 1) are presented in Table 3, and the simulated trajectory of the OS and the TSs is shown in Figure 7.

Table 3. Ship parameters in the scenario of Case 1.

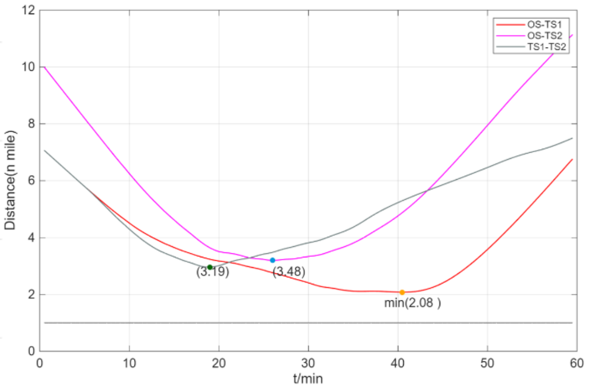
	Position	**Course/ °**	**Speed/kn**	**Goal**
OS	(0, −1)	000	15	(0, 9)
TS1	(5, 4)	270	15	(−5, 4)
TS2	(0, 9)	180	15	(−1, 0)

The situation is a starboard-crossing and head-on where exists a collision hazard between TSs. In this experiment, responsibility (*Res*) of OS was set as (1,1), the responsibilities (*Res*) of TSs were set as (0,1). Figure 7b,c respectively illustrates the real-time distance between ships and the variation of CPA. In Figure 7c, the red line denotes the CPA_1 value between OS and TS1, the pink line denotes the CPA_2 value between OS and TS2, and the green line signifies the CPA_s value between TS1 and TS2. In the figure, at t = 0 min, the CPA between all ships is 0 n miles, indicating that there is a mutual collision hazard among the ships in scenario. At t = 4 min, all ships in the scenario adopt a starboard-turning avoiding collision maneuver in compliance with the COLREGs under the MVO-IDWA algorithm. When 18 min, the TS1 and TS2 meet with their CPA with 3.19 n miles; subsequently, the OS and TS2 arrive at their CPA at 3.48 n miles, while the min encounter distance between OS and TS1 is 2.08 n miles. The OS reaches the destination point and reduce speed to 0 kn at t = 54 min.

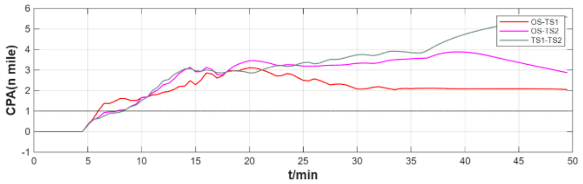
t(/min)



(a) Multi-ship Encounter Situation Simulation Results



(b) Ship Distance Variation Chart



(c) Ship CPA Variation Chart

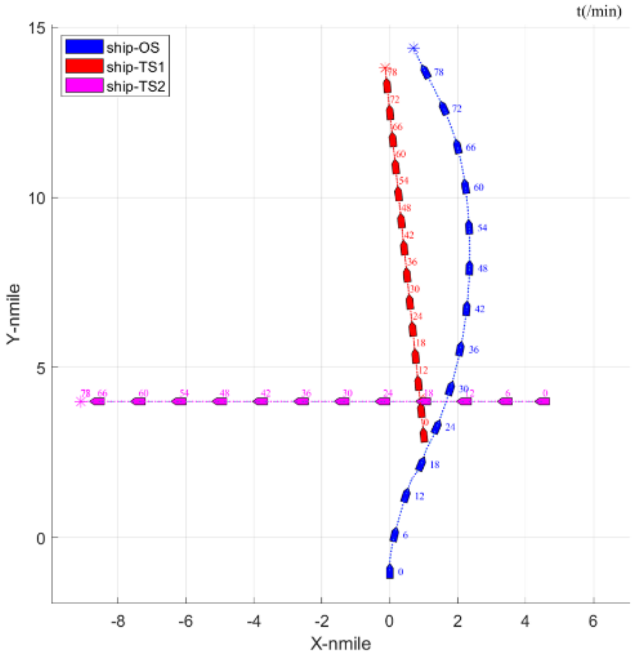
Figure 7. Multi-ship simulated trajectory of Case 1.

4.2. Case 2: three-ship encounter scenario, there is no collision hazard between the TSs

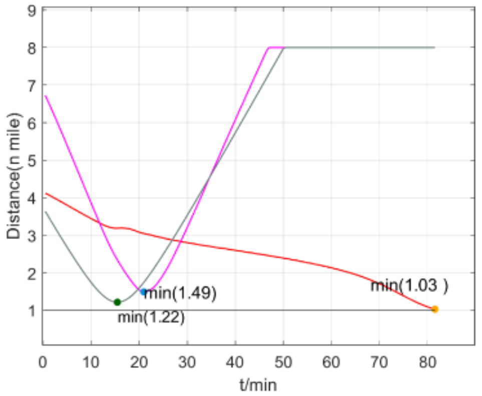
The original parameters of all ships in Case 2 are presented in Table 4, and the simulated avoiding collision trajectories of the OS and the TSs are illustrated by Figure 8. The encounter scenario corresponds to a starboard-crossing and overtaking situation, where no collision risk exists between the TSs. There exist only two pairs of give-way and stand-on obligations within this scenario. The Res of OS was set as (1,1) and that of TSs as 0 in this experiment. Figure 8b,c depicts the real-time encounter distances between ships and the variation values of the CPA, respectively.

Table 4. Ship parameters in the scenario of Case 2.

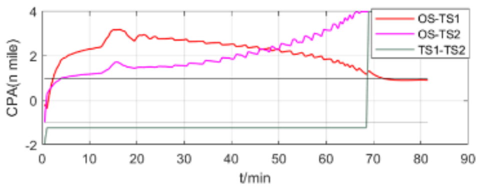
	Position	Course/ °	Speed/kn	Goal
OS	(0, −1)	000	12	(0, 15)
TS1	(2, 2)	354	8	(−1.3, 13.5)
TS2	(5, 5)	270	12	(−7, 5)



(a) Multi-ship Encounter Situation Simulation Results



(b) Ship Distance Variation Chart



(c) Ship CPA Variation Chart

Figure 8. Multi-ship simulated trajectory of Case 2.

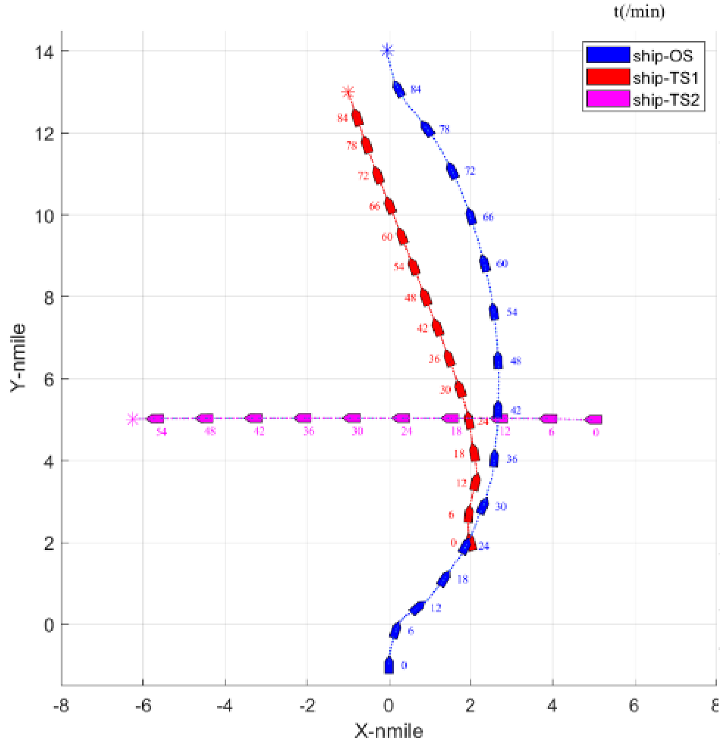
In Figure 8c, when 0 min, |CPAS| > 1 n mile, indicating that no collision risk exists between TS_1 and TS_2. In contrast, the absolute values of CPA1 and CPA2 are less than 1 n mile, which means the OS is at collision risk with TS_1 and TS_2 respectively and acts to keep out of the way. Under the MVO-IDWA algorithm, the OS takes avoiding collision decision in compliance with the COLREGs by turning to starboard. When 20 min, the min encounter distance between the OS and TS_2 reaches 1.49 n mile. When 80 min, the OS arrives at the destination point; meanwhile, it completes the overtaking of TS_1, with the min distance reaching 1.03 n mile.

4.3. Case 3: three-ships encounter scenario, there is collision risk between TSs

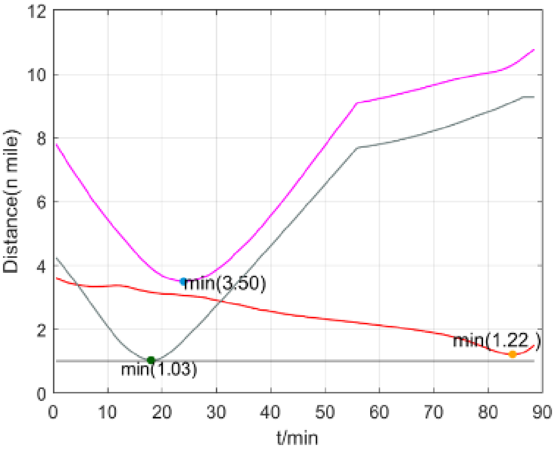
The original parameters of all ships in Case 3 are presented in Table 5, and the simulated encounter trajectories of the OS and the TSs are illustrated by Figure 9. The multi-ship scenario corresponds to a starboard-crossing and overtaking situation, where a collision hazard exists between TS_1 and TS_2, and three pairs of stand-on and give-way obligations are defined within this scenario. Figure 9b,c depict the real-time encounter distances between ships and the variation values of CPA, respectively.

Table 5. Ship parameters in the scenario of Case 3.

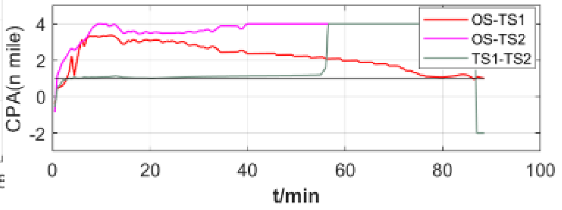
	Position	Course/ °	Speed/kn	Goal
OS	(0, −1)	000	12	(0, 15)
TS1	(1, 3)	354	8	(−0.25, 15)
TS2	(4.5, 5)	270	12	(−10, 4)



(a) Multi-ship Encounter Situation Simulation Results



(b) Ship Distance Variation Chart



(c) Ship CPA Variation Chart

Figure 9. Multi-ship simulated trajectory of Case 3.

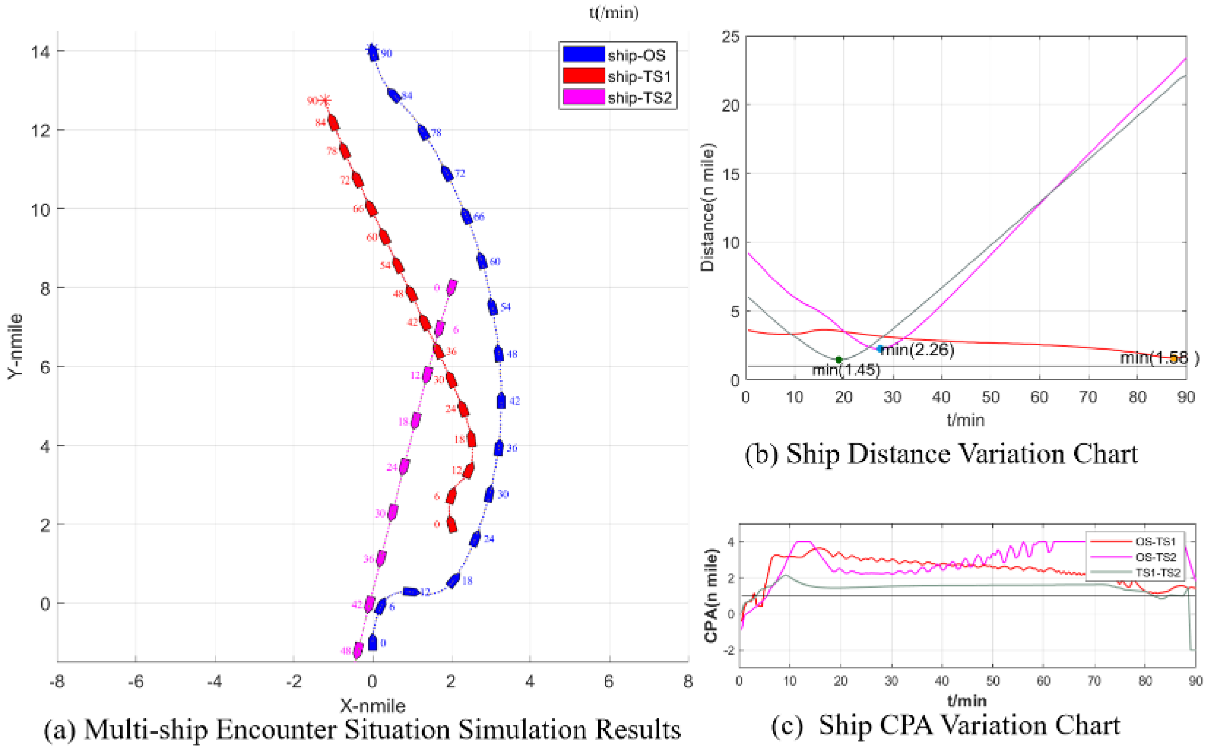
In this figure, at t = 0 min, the values of CPA1, CPA2 and CPAS are all less than 1 n mile, indicating that there is a collision hazard between all ships in the scenario. Judging from the starting points, the OS is overtaking TS_1 and in crossing with TS_2, thus assuming the obligation to give way to TSs. TS_1 and TS_2 are in a crossing situation, where TS_1 needs keep out of the way. The Res of OS was set as (1,1), the Res of TS1 as (1,0) and that of TS2 as (0,0) in this experiment. There exist three pairs of give-way and stand-on obligations within this scenario. Under the MVO-IDWA algorithm, both the OS and TSs take corresponding collision avoidance actions. The OS needs to give greater consideration to the maneuver of TS_1, make a large starboard turn in compliance with the COLREGs for collision avoidance, and leave a certain maneuvering space for TS_1. At t = 18 min, after TS_1 and TS_2 reach their min encounter distance of 1.03 n mile, TS_1 resumes its original course. When 84 min, the OS and TS_1 meet with their min distance of 1.22 n mile. During the process of avoiding TS_1, the OS and TS_2 meet with their min distance of 3.5 n mile at t = 23 min.

4.4. Case 4: three-ships encounter scenario, there is collision risk between TSs

The original parameters of all ships in Case 4 are presented in Table 6, and the simulated collision avoidance trajectories of OS and the TSs are illustrated by Figure 10. The encounter situation corresponds to a head-on and overtaking situation, where a collision hazard exists between the TSs. Despite the differences in the encounter situations between the ships in multi-ship scenario, the OS bears the same obligations as those in Case 3, and there are three pairs of give-way and stand-on obligations defined within this scenario. The Res of OS was set as (1,1), the Res of TS1 as (1,0) and that of TS2 as (1,0) in this experiment. Specifically, Figure 10b,c depicts the real-time encounter distances between ships and the variation values of the CPA, respectively.

Table 6. Ship parameters in the scenario of Case 4.

	Position	Course/ °	Speed/kn	Goal
OS	(0, −1)	000	12	(0, 15)
TS1	(2, 2)	344	8	(−1.7, 13.5)
TS2	(2, 8)	198	12	(−4.3, −17.4)



(a) Multi-ship Encounter Situation Simulation Results

(b) Ship Distance Variation Chart

(c) Ship CPA Variation Chart

Figure 10. Multi-ship simulated trajectory of Case 4.

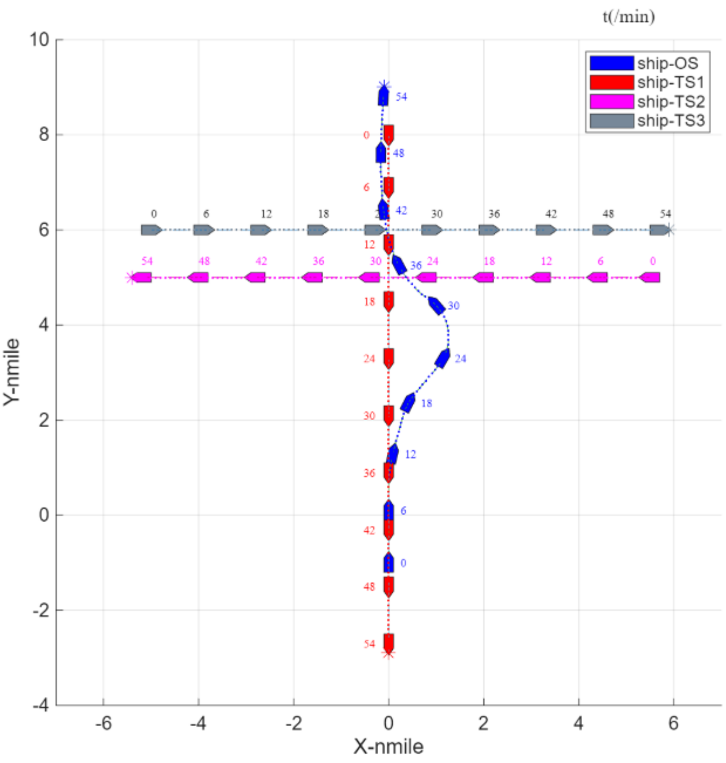
In this figure, at t = 0 min, the values of CPA1, CPA2 and CPAS are all less than 1 n mile, meaning that a collision risk exists between all ships. Judging from the starting positions, the OS is overtaking TS_1 and in a head-on situation with TS_2, thus assuming the obligation to keep clear of TSs; TS_1 and TS_2 are in a starboard-crossing situation, and TS_1 is also designated as the give-way ship. Under the MVO-IDWA algorithm, both the OS and TSs take corresponding collision avoidance actions. The OS needs to give greater consideration to the maneuver of TS_1, execute a large starboard turn to avoid collision in compliance with the COLREGs, and reserve a certain maneuvering space for TS_1. Specifically, OS first keeps clear of TS_1 while avoiding the collision risk with TS_2, which enables TS_2 to prioritize its stand-on obligations and thus maintain its course and speed. At t = 18 min, after TS_1 and TS_2 reach their min distance of 1.45 n mile, TS_1 resumes its original course. When 84 min, the OS and TS_1 meet with their min distance of 1.58 n mile. During the process of avoiding TS_1, the OS and TS_2 meet with their min distance of 2.26 n mile at t = 28 min.

4.5. Case 5: complex multi-ship encounter scenario

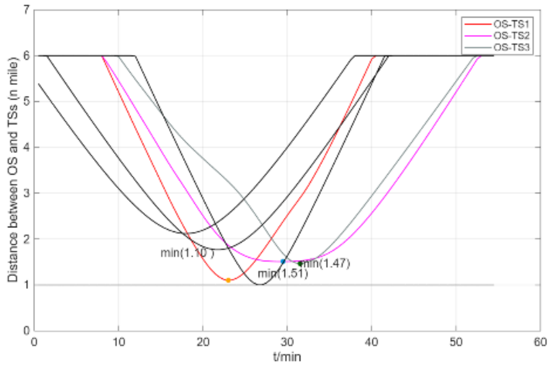
The initial ship parameters in this experiment (Case 5) are presented in Table 7. There is a collision risk between the OS and TSs within this encounter scenario, whereas no collision risk exists among the TSs. Specifically, the OS encounters TS1 in a head-on situation and TS2 in a small angle starboard crossing situation, where the OS is designated as the give-way vessel. Meanwhile, TS3 is located on the port side of the OS. In the Figure 11, at t = 8 min, guided by the MVO-IDWA algorithm, the OS executes a starboard turning maneuver for collision avoidance in compliance with COLREGs. At t = 30 min, the OS safely passes astern of TS3 and resumes its original course. Figure 11b presents the distance variations between ships during the encounter scenario, while Figure 11c illustrates the detailed navigation parameters of the OS throughout the voyage, including the course variation, speed variation and yaw rate variation of the OS.

Table 7. Ship parameters in the multi-ship encounter situation of Case 5.

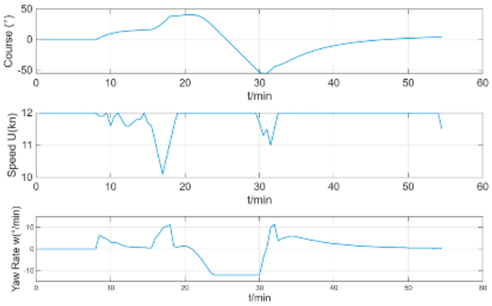
	Position	Course/ °	Speed/kn	Goal
OS	(0, −1)	000	12	(0, 15)
TS1	(0, 8)	180	12	(−3, 0)
TS2	(5.5, 5)	270	12	(−6, 5)
TS3	(−5, 6)	90	12	(6.5, 6)



(a) Multi-ship Encounter Situation Simulation Results



(b) Ship Distance Variation Chart



(c) Own ship Real-time Data in Case 5

Figure 11. Vessel route chart for complex encounter situations of Case 5.

To further assess the computational feasibility of the MVO-IDWA algorithm for real-time onboard deployment, the total simulation runtime for each case is recorded and summarized in Table 8.

Table 8. Computational cost of MVO-IDWA algorithm across simulation cases.

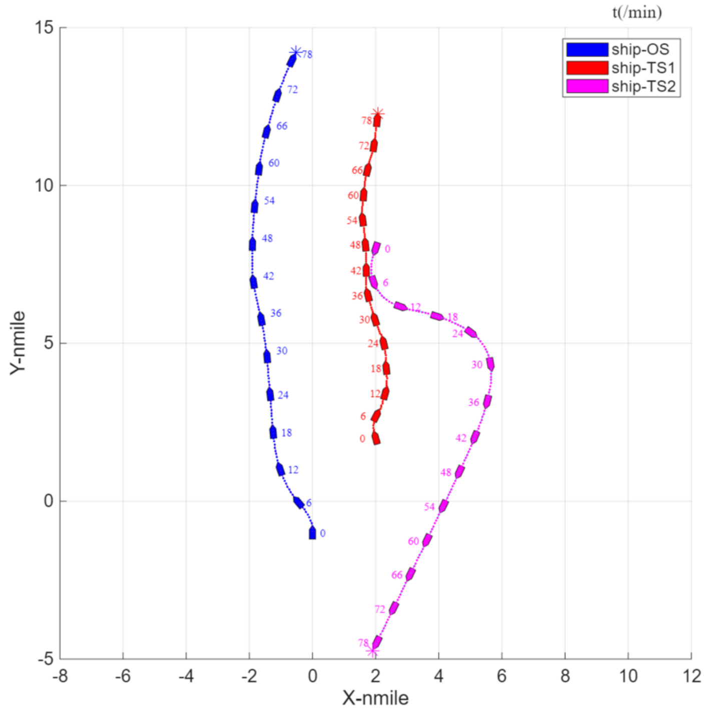
Case 1	Case 2	Case 3	Case 4	Case 5
130.5 s	176.5 s	246.2 s	236 s	197 s

4.6. Control experiment

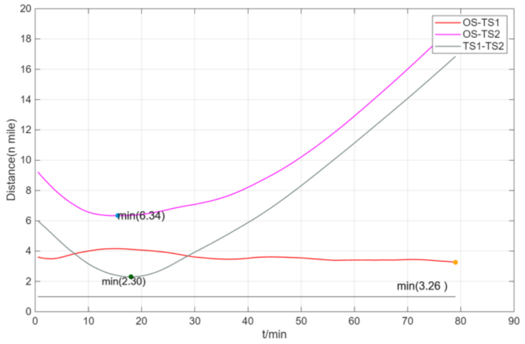
4.6.1. Ablation experiment for the responsibility allocation mechanism

The original parameters of all ships in ablation experiment are adopted from Case 4. In contrast, all ships in this experiment are simulated using the MVO-IDWA algorithm excluding the COLREGs responsibility assignment mechanism. Specifically, the responsibility screening for the ACC in the velocity space is eliminated, and the COLREGs compliance term *Col*(v,w) in the evaluation function is disabled.

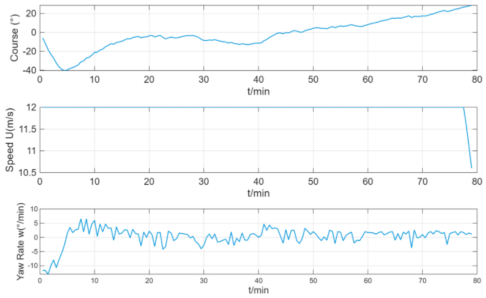
The experimental results are shown in the Figure 12. There exists a risk of collision among all ships in the scenario. At t = 0 min, the OS is in an overtaking situation with TS1 and a head-on situation with TS2, where the OS bears the give-way vessel responsibility in both situations. Meanwhile, TS1 and TS2 form a crossing situation, with TS1 acting as the give-way vessel. With the removal of the responsibility assignment mechanism, TS2, which should maintain its course and speed, instead executes a large-angle left turn to avoid TS1. After TS1 and TS2 complete the passing and clearing maneuver, the OS is still in the process of overtaking TS1. It can be observed from the results that TS1, as the stand-on vessel, still makes a slight right turn to yield to the OS. Therefore, although the MVO-IDWA algorithm without the responsibility assignment mechanism can guarantee navigation safety between vessels, the resulting collision avoidance behaviors fail to comply with the COLREGs regulations. Figure 12b presents the distance variations between ships during the encounter scenario, while Figure 12c illustrates the detailed navigation parameters of the OS throughout the voyage, including the course variation, speed variation and yaw rate variation of the OS.



(a) Multi-ship Encounter Situation Simulation Results



(b) Ship Distance Variation Chart

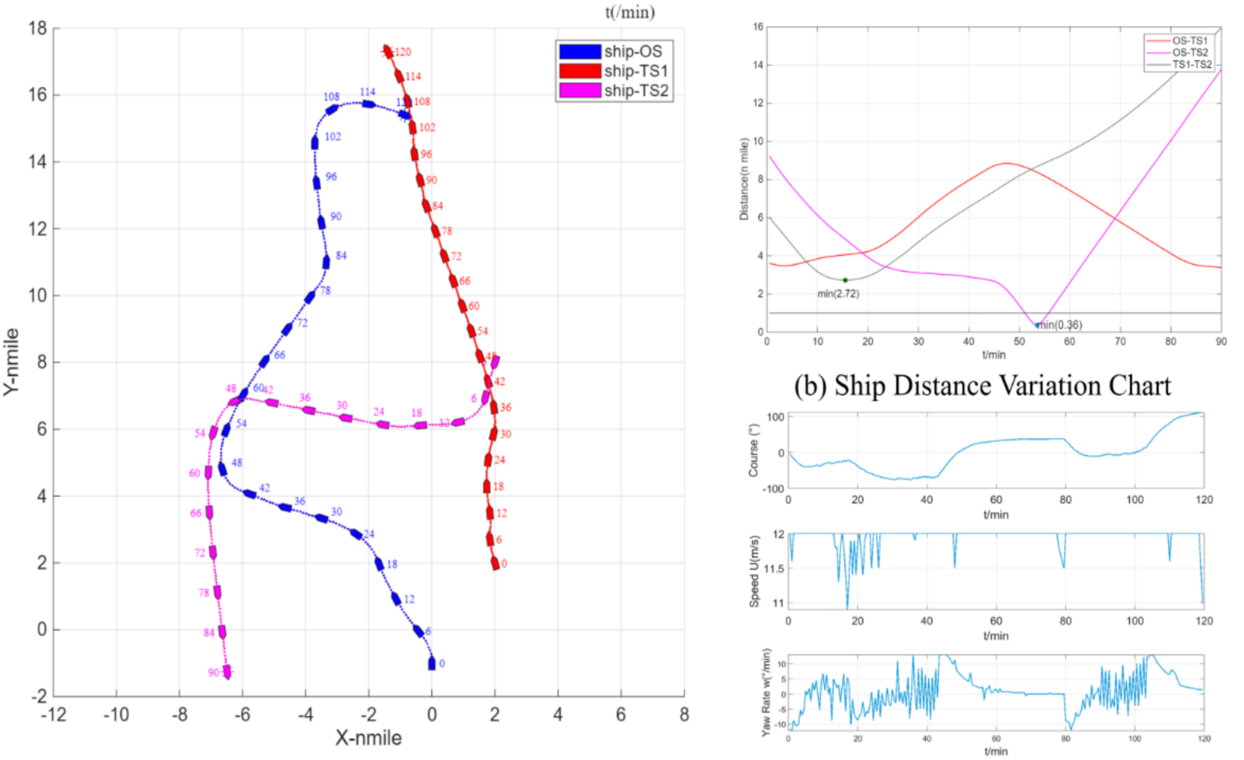


(c) Own ship Real-time Data in Ablation Experiment

Figure 12. Multi-ship simulated trajectory of ablation experiment.

4.6.2. Control experiment with standard DWA

In the comparative experiment of the standard DWA algorithm, the initial parameter settings of Case 4 are adopted for the raw data of all ships. The experimental results are shown in the Figure 13. In the encounter scenario, collision risks exist among all ships. Due to the standard DWA algorithm, the OS chooses to turn to port to move away from TS2, whereas TS1 turns to starboard under the action of the standard DWA algorithm, as collision risks also exist between TS1 and TS2. As time progresses, both the OS and TS2 deviate from their paths to avoid TS1. Since OS turns to port and TS2 turns to starboard, their avoidance trajectories converge, putting the two vessels in a dangerous situation and leading to a collision deadlock. While maneuvering to avoid collisions with other ships, the OS finally performs an extremely dangerous collision-avoidance action at t = 48 min by making a sharp turn to starboard. In Figure 13b, the closest distance of approach between the OS and TS2 is 0.36 n miles. While Figure 13c illustrates the detailed navigation parameters of the OS throughout the voyage, including the course variation, speed variation and yaw rate variation of the OS.



(a) Multi-ship Encounter Situation Simulation Results

(b) Ship Distance Variation Chart

(c) Own ship Real-time Data with Standard DWA

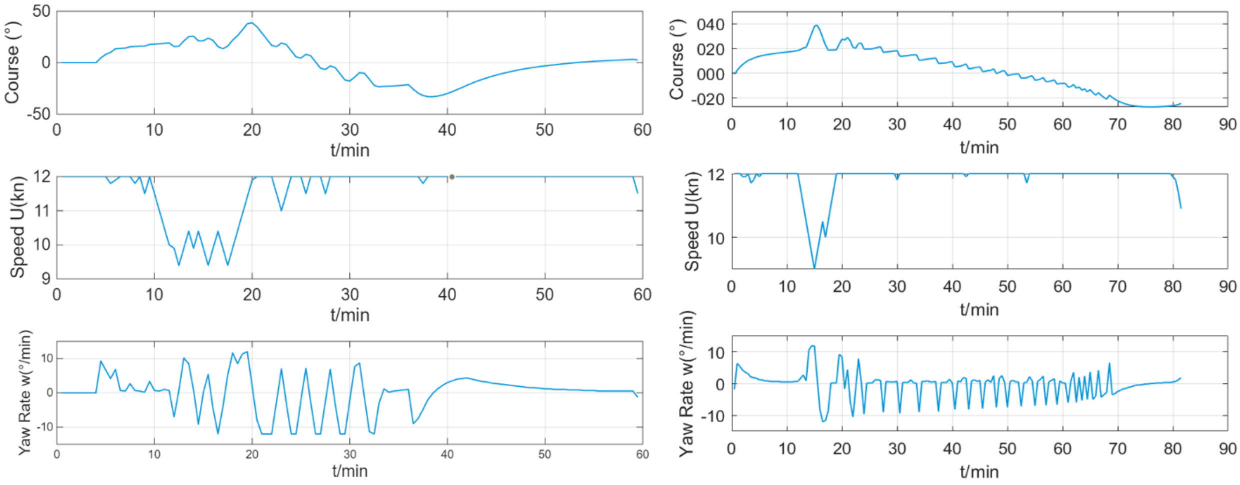
Figure 13. Multi-ship simulated trajectory with standard DWA.

4.7. Discussion

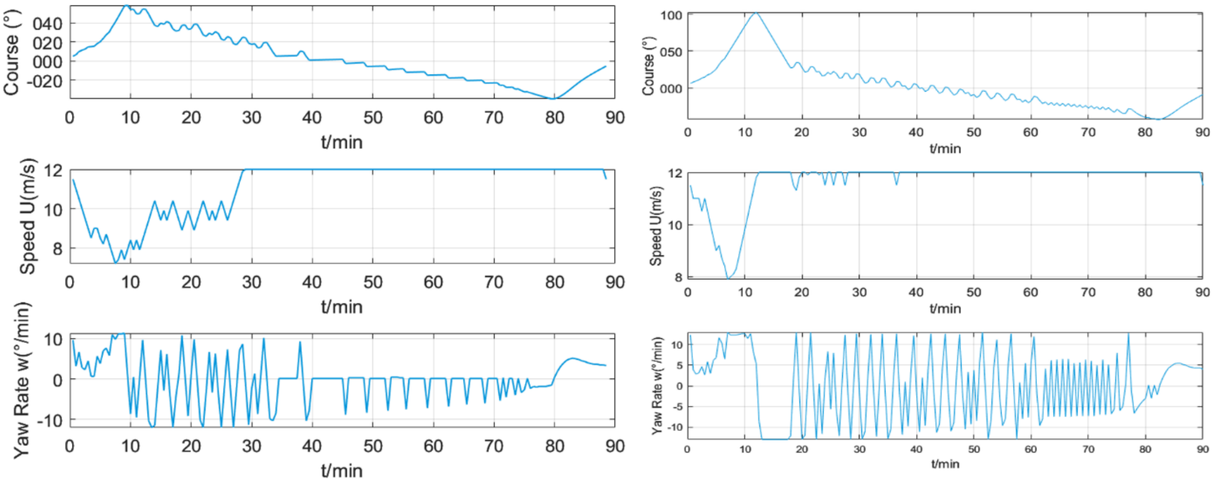
In the complex encounter avoidance experiment, the detailed parameters of OS’s navigation process in experimental Cases 1 to 4 shows in the Figure 14, including the changes in OS’s heading, speed, and heading changing rate.

In Case 1, the OS and TSs in the encounter scenario both obligated to give way to each other. The OS is in a crossing encounter situation with TS1, and in a head-on encounter situation with TS2. Under the influence of the MVO-IDWA algorithm, each ship in the scenario can take actions for avoiding collision that comply with the COLREGs.

In Cases 2 and 3, the OS and the TSs form situations of overtaking and starboard crossing at small angles. The difference between the two cases lies in whether a collision risk exists between the TSs. In Case 2, there is no collision risk between the TSs, and the scenario involves two pairs of give-way and stand-on vessel responsibilities. the OS is assigned the give-way vessel responsibility, while all TSs in the scenario are stand-on vessels that maintain their course and speed, with OS bearing *Res* (1, 1) and both TSs bearing *Res* = 0. In Case 3, however, a collision risk exists between the TSs, resulting in three pairs of give-way and stand-on vessel responsibilities in the scenario, OS as *Res* = (1, 1), TS_1 as *Res* = (1, 0), and TS_2 as *Res* = (0, 0). Besides the OS acting as a give-way vessel, one of the TSs also bears the give-way obligation. Accordingly, in Case 3, when the OS takes evasive action against other vessels, it must continuously account for changes in the heading and speed of those vessels to ensure the safety of its own route.



(1) Own Ship Real-Time Control Data in Case 1 (2) Own Ship Real-Time Control Data in Case 2



(3) Own Ship Real-Time Control Data in Case 3 (4) Own Ship Real-Time Control Data in Case 4

Figure 14. Real-Time operational data of OS in multi-ship encounter situation of Case 1–4.

In Case 2, the OS can plan its avoidance maneuver without accounting for inter-TS dynamics, allowing for a relatively moderate starboard turn. In Case 3, the OS must additionally reserve maneuvering space for TS_1—which bears give-way responsibility toward TS_2—necessitating a larger and more sustained course alteration, as reflected in the greater heading deviation and more volatile rate-of-change observed in Figure 14c compared to Figure 14b. A comparative analysis of the OS's real-time maneuvering data in Case 2 and Case 3 shows Figure 14b,c, that the OS's heading and speed changes in Case 3 are significantly larger than those in Case 2, and the duration of these changes is longer. Additionally, the rate of change in heading in Case 3 is more volatile than in Case 2.

In Case 4, the OS keeps clear of TSs, and there is a dangerous situation between the TSs. Therefore, when the OS takes action, it must consider leaving enough space for the TSs, which as the give way ship. The comparison shows that the MVO-IDWA algorithm takes into account the impact of the dangerous behavior among TSs on the OS's decision-making, verifying that the algorithm considers the division of responsibility in complex encounter scenarios and the impact of dynamic changes in the TSs.

From the real-time maneuvering data of the OS in Cases 1 to 4, it can be observed that when both heading and speed change simultaneously, there is a discontinuity in speed changes and an issue with an unsmooth adjustment process in the decision-making, making it difficult for the TS to detect the trend of the OS's speed variations, leads to jitter in the CPA between the OS and TS in the scenario. This problem may be related to the settings of the evaluation function parameters and the logical design. Additionally, the existing MVO-IDWA algorithm does not take into account the ship's motion mathematical model or the executable status of the ship's propulsion system. Therefore, future research will focus on optimizing the evaluation function design and incorporating the ship's motion characteristics and propulsion system constraints into the upcoming research.

5. Conclusion

Autonomous avoiding collision decision-making is a core component of ship autonomous navigation, particularly crucial in complex multi-ship encounter scenarios. This study proposes a collision risk identification method based on the VO, constructs a classification framework for complex multi-ship encounter scenarios, further clarifies the COLREGs for the division of navigational responsibilities between encountering ships, takes into account the dangerous situations between TSs in the scenario, and integrates these responsibilities into the DWA collision avoidance algorithm to develop the MVO-IDWA algorithm.

This method provides an integrated modular algorithm framework that can be embedded into existing ship autonomous systems, enabling collision avoidance decisions in compliance with regulations without relying on the cooperation of TSs. Its approach to danger perception and responsibility allocation offers reproducible simulation benchmarks for subsequent regulatory compliance testing of MASS and scenario library development. Additionally, the integration of danger and responsibility can be adopted by Vessel VTS or shore-based monitoring platforms to proactively identify multi-ship responsibility conflicts and issue early warnings.

Future research should incorporate these environmental impacts into the ship trajectory simulation module of the algorithm to enhance the safety of its optimal decision-making outputs. At present, the design of weight parameters in the improved MVO-IDWA algorithm lacks theoretical justification, and the underlying mathematical mechanisms remain insufficiently explored. Future work may optimize the variability of these parameters to better align with practical maritime navigation requirements.

In addition, to bridge the gap between the decision-making layer and the physical execution layer of the ship, future work will extend the MVO-IDWA framework along the following four directions. First, the framework will be coupled with an MMG-type 3-DOF maneuvering model to represent ship hydrodynamics more realistically. Second, actuator constraints will be incorporated, including rudder angle and rate limits and propeller response dynamics. Third, environmental disturbances including wind, currents, and waves will be incorporated into the trajectory simulation module, thus supplementing the environmental modeling framework elaborated in the preceding sections. Finally, the dynamic realizability of the commanded trajectories will be evaluated using tracking-error statistics between commanded and executed trajectories, together with heading and speed-change-rate statistics and CPA jitter amplitude, thereby providing a quantitative characterization of the trade-off between command smoothness and avoidance efficiency.

Data availability statement

No supplementary or additional data were generated in this study.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. Specifically, the authors used ChatGPT for language polishing and text revision only. The authors take full responsibility for the entire content of the manuscript.

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Authors' contribution

Conceptualization, X.M. and H.L.; methodology, X.M.; software, X.M.; validation, H.L., G.T. and T.G.; formal analysis, X.M.; investigation, X.K.; resources, H.L.; data curation, G.T.; writing—original draft preparation, X.M.; writing—review and editing, H.L.; visualization, X.M.; supervision, Y.Y.; project administration, H.L.; funding acquisition, H.L. and Y.Y. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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