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RESEARCH ARTICLE

A collaborative collision avoidance strategy for autonomous ships under mixed scenarios

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Abstract

Ship collision avoidance has always been one of the classic topics in the field of marine research. In traditional encounter situations, officers on watch (OOWs) usually use a very high frequency (VHF) radio to coordinate each other. In recent years, with the continuous development of autonomous ships, there will be a mixed situation where ships of different levels of autonomy coexist at the same time. Under such a scenario, different decision makers have different perceptions of the current scene and different decision-making logic, so conventional collision avoidance methods may not be applicable. Therefore, this paper proposes a collaborative collision avoidance strategy for multi-ship collision avoidance under mixed scenarios. It builds a multi-ship cooperative network to determine cooperative objects and timing, at the same time. Based on a cooperative game model, a global collision avoidance responsibility distribution that satisfies group rationality and individual rationality is realised, and finally achieves a collaborative strategy according to the generalised reciprocal velocity obstacle (GRVO) algorithm. Case studies show that the strategy proposed in this paper can make all ships pass each other clearly and safely.

1. Introduction

1.1. *Background*

In recent years, the autonomous ship has gradually become a hot research topic around world. An autonomous ship involves a highly integrated development of ship navigation intelligence and informatisation. Antão and Guedes Soares (2008) pointed out that 75% to 96% of marine accidents and causalities result from some type of human error. An autonomous ship can help or replace an officer on watch (OOW) to make a series of navigation decisions, which can overcome errors caused by human factors and reduce the probability of marine accidents (Zhang et al., 2021a). At the same time, a shortage of 147,500 skilled seafarers is predicted by 2025 (Lušić et al., 2019), and the high intelligence level of an autonomous ship can reduce the number of seafarers required. In addition, from the perspective of shipowners' operating costs, an autonomous ship can save on seafarers' wages and, at the same time, allows the conversion of the original seafarers' cabins into cargo warehouses, thereby increasing the volume available for cargo transportation (Bakdi et al., 2021).

The autonomous navigation system (ANS) is the brain of a maritime autonomous surface ship (MASS) and plays a critical role throughout the system. ANS makes a series of navigation decisions in real time based on external information (Wang et al., 2020). Among them, collision avoidance is one of the primary tasks faced by an autonomous navigation system (Huang et al., 2020; Zhang et al., 2021b). Ship collision avoidance is not a new topic. As early as the 1990s (Calvert, 1997), researchers proposed collision avoidance models for different scenarios. In the past few decades, the field of ship collision avoidance has emerged and accumulated rich research results (Tam et al., 2009). However, most of the existing collision avoidance strategies follow the 'proactive strategy', that is, the design subject of the collision avoidance model undertakes almost all evasive actions. This will increase the cost of navigation and, at the same time, unilaterally formulating a collision avoidance strategy will become 'wilful', resulting in an uncoordinated situation during the collision avoidance process, which is not in line with the actual traffic conditions at sea. Under a real collision avoidance process, OOWs usually use a very high frequency (VHF) radio to confirm each other's intentions and coordinate evasive actions (Szlapczynski and Szlapczynska, 2016). The lack of human involvement on the bridge of an autonomous ship creates challenges for the coordination of collision avoidance actions (Aylward et al., 2022; Zhang et al., 2022a).

The development of MASS should be a gradual process, as it will make a difference in the degree of intelligence and autonomy of a ship (Pedersen et al., 2020). In the future, each participant under the same collision avoidance scenario will show typical multi-modal characteristics: traditional ships, ships equipped with auxiliary decision-making systems, remote-controlled ships and autonomous ships coexisting at the same time (Ventikos et al., 2020). Under such mixed scenarios, different decision-making subjects have different perceptions of the current marine scene and different decision-making logic. At the same time, there is a strong interactive coupling between different decision-making units, the same target ship (TS) may be participating in other collision avoidance scenarios while forming an encounter situation with own ship (OS), which leaves a high degree of uncertainty of any TS's evasive action. Therefore, considering the particularity of mixed scenarios formed by ships with different autonomy levels, this paper attempts to propose a multi-ship collaborative collision avoidance strategy under mixed scenarios so as to further ensure the safety of an autonomous ship.

1.2. Related works

In this part, the related work is summarised into three aspects, including a general proactive ship collision avoidance method, a centralised ship collaborative collision avoidance method, and a distributed ship collaborative collision avoidance method.

(1) General proactive ship collision avoidance method.

A lot of valuable research has been carried out on autonomous ship collision avoidance decision-making. The concepts, techniques and key points of ship collision avoidance have been summarised in some literature reviews (Statheros et al., 2008; Tam et al., 2009; Huang et al., 2020). With the continuous development of intelligent unmanned technology, the obstacle avoidance theory of unmanned systems gradually migrated to the marine field. Researchers have designed many new collision avoidance algorithms and achieved good results, such as the improved artificial potential field (APF) (Xue et al., 2011; Lyu and Yin, 2019), the dynamic window (DW) (Wilthil et al., 2018), the modified model predictive control (MPC) (Johansen et al., 2016; Xie et al., 2019) and the velocity obstacle method (Kuwata et al., 2013; Zhao et al., 2016; Shaobo et al., 2020). It is also worth noting that methods based on deep reinforcement learning have become popular in recent years (Shen et al., 2019; Zhao and Roh, 2019), and also the analysis and processing method based on big data, such as the automatic identification system (AIS) (Zhang et al., 2022b, 2023). As mentioned above, the goal of the proactive ship collision avoidance method is to ensure ship safety as much as possible, so most algorithms do not consider the issue of coordination between ships, and they prefer to make decisions and take actions independently.

(1) Centralised ship collaborative collision avoidance method.

The centralised method means that all ships will be coordinated by a unified central station from a global perspective (Akdağ et al., 2022a). The goal of this method is to find the global optimal solution.

Notably, this type of approach is based on a strong assumption, namely all ships are subject to the control of the central station. The centralised method is more suitable for the scheduling of the vessel traffic service (VTS) centre. Multi-objective optimisation algorithms are more suitable for solving such problems. Tam and Bucknall (2013) developed a deterministic collision avoidance path planning algorithm to provide collision-free paths for all involved ships, assuming that all encountering ships are in a cooperative mode. Liu et al. (2016) proposed a hybrid optimisation cultural algorithm (CA) based on the particle swarm optimisation and bacterial foraging algorithm. Szlapczynski and Szlapczynska (2012) presented a multi-ship trajectory planning method by using evolutionary algorithms. Li et al. (2019a) proposed a rolling horizon optimisation approach for multiple ships from a global optimal perspective, with the aim to minimise the time costs and course angle alterations of the anti-collision operations. For multi-ship collision avoidance under mixed scenarios, we cannot guarantee that each ship with different thinking will implement the global optimal solution strictly. Because the global optimal is not the individual optimal, such a strategy is unrealistic to execute without strong constraints.

(1) Distributed ship coordinated collision avoidance method.

The distributed method allows for different intelligent agents calculating their own decisions at the same time. This decentralised approach makes the collaborative collision avoidance process no longer dependent on the central station and improves the robustness of the decision-making system. Zhang et al. (2015) presented a distributed multi-ship collision avoidance decision support formulation under the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), in which all the involved ships in this algorithm can make a decision individually and obey the basic principles of the COLREGS. Kim et al. (2015) use a distributed local search algorithm (DLSA) and a distributed tabu search algorithm (DTSA) to find optimal courses for involved ships. Li et al. (2019b) proposed a distributed coordination strategy to deal with the many-to-many ship collision avoidance problem, where an optimisation strategy is adopted to find the most efficient collision avoidance plan for ships, namely, the rudder angles that each ship should take, and the corresponding operation time for rudder steering. Wang et al. (2020) proposed a novel scheme called ‘observation-inference-prediction-decision (OIPD)’. OIPD is used for the distributed multi-ship collision avoidance problem with consideration of the autonomous, dynamic nature of the real circumstance. Li et al. (2020) used a distributed algorithm to communicate the entire collision avoidance trajectory information for each ship. Akdağ et al. (2022b) used the scenario-based model predictive control method to realise collaborative collision avoidance. The distributed method is still based on some assumptions that all decision-makers are intelligent agents with the same decision-making logic or the OS can know the trajectory of TSs in advance. For the mixed scenario, which is discussed above, the distributed method still has its own limitations.

1.3. Motivation and contributions

Based on the above discussions, most of the current multi-ship collision avoidance decision-making models are more inclined to actively avoid other TSs from the perspective of the OS. Under such a strategy, the OS always yields to other ships. This mode will not only cause greater off-course cost, but also uncoordinated collision avoidance scenarios, which will affect the safety of ship navigation. Moreover, these two typical multi-ship cooperative collision avoidance algorithms, namely ‘distributed’ and ‘centralised’, also have their own limitations. The distributed method requires all ships to adopt a consistent collision avoidance model, which is mainly suitable for scenarios such as the cluster control of multi-unmanned ship. The goal of the centralised method is to achieve the global optimal solution, requiring each ship to obey decision-making instructions, which is mainly used in centralised command and dispatch scenarios such as VTS. Autonomous ships that behave in a more human-like manner have always been the goal of researchers. At present, most ships that are in danger of collision need to communicate and coordinate through a VHF radio to ensure the consistent collision avoidance actions. Therefore, considering ‘collaborative’ in decision-making models will be one of the main research directions of collision avoidance algorithms in the future.

However, the mixed multi-ship collision avoidance scenario is different from the general scenario. There are different ships with different levels of autonomy under the same ‘mixed scenarios’, so that the OOWs on various ship bridge or the collision avoidance algorithms adopted in different ANS always have their own unique strategies, which brings challenges to multi-ship collaborative collision avoidance under mixed scenarios. The biggest feature of the mixed scenario is that each decision-making participant has a different collision avoidance logic. The key to realise collaborative collision avoidance between ships under a mixed scenario is how to make all participants reach a consensus on this collaborative collision avoidance strategy. The consensus-based collaborative collision avoidance strategy is not necessarily the global optimal solution, but it should be a binding and fair strategy that can prompt all ships to act according to the agreement.

Therefore, a collaborative collision avoidance strategy for autonomous ships under mixed scenarios is envisioned in this paper. Under this strategy, the cooperative objects and timing are determined, and then the cooperative network is constructed. Then, based on the cooperative game theory, the collision avoidance responsibilities of different ships under the same mixed scenario are evaluated, and the cooperative strategy is finally generated. Under this special mixed scenario, autonomous ships can not only generate collision avoidance decisions for themselves, but also can create some corresponding action expectations for other ships. This collaborative strategy can satisfy group rationality and individual rationality, and also can provide a basis for the negotiation between multi-ship collision avoidance.

1.4. Outlines

The structure of this paper is as follows. The methodology for making collaborative collision avoidance strategies is described in detail in Section 2. A case study (including two different scenarios) is shown in Section 3. Section 4 includes discussions on the performance of this strategy. Conclusions are summarised in Section 5.

2. Methodology and modelling

The framework of the model proposed in this paper is shown in Figure 1. According to the ships’ initial state information and COLREGS, the collision risk matrix and encounter situation matrix between ships can be calculated, and the collaborative collision avoidance network of this mixed scenario can be formed. After that, according to the cooperative game model, the collision avoidance responsibility of each ship is divided, and the collaborative decisions are calculated according to GRVO and delivered to each ship for execution.

2.1. Construction of collaborative collision avoidance network

Due to the different levels of ship autonomy, each ship under the mixed scenario has its own understanding of the current situation. To formulate a collaborative collision avoidance strategy between multi-modal ships at sea, it is first necessary to determine a relatively objective calculation method to identify the objects that need to be collaborative and the timing of collaboration in mixed scenarios, build a reasonable collaborative network, and improve the quality of collaboration. In other words, it is necessary to find ships that are currently related to each other in the space centred on the OS, and they may be directly related or indirectly related (through other ships). In this section, we propose a method for constructing a collaborative collision avoidance network under mixed scenarios, which is calculated by a double-matrix model, the collision risk matrix, and the encounter situation matrix. Ship collision risk creates connections between different ships, and the encounters define these connections. At the same time, according to the requirements of the relevant clauses of COLREGS (1972), collision risk is the prerequisite for the formation of the encounter situation, so the collision risk matrix is directly related to the encounter situation matrix (Wang et al., 2021).

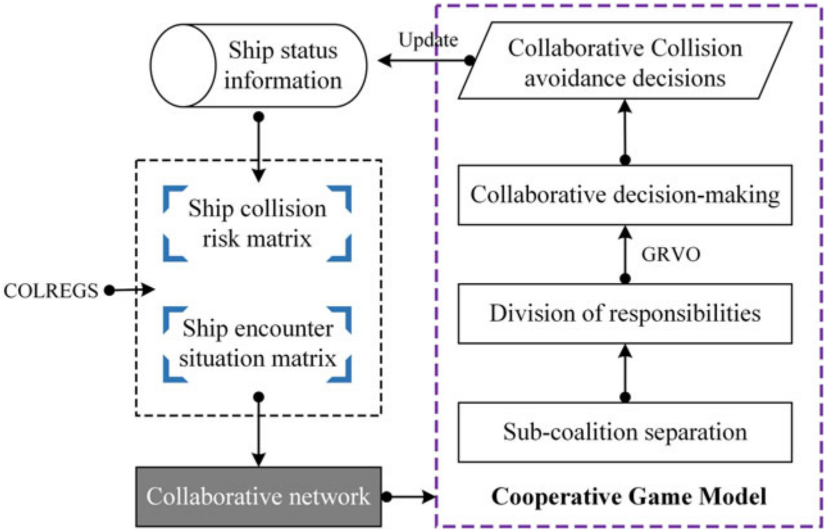


Figure 1. *A framework for collaborative collision avoidance decision-making method under mixed scenarios.*

First, define ξ as the scene composed of all ships within a radius of 12 nautical miles centred on the OS, as shown in Equation (1), the scene ξ contains $n + 1$ ships in total:

$$\xi = \mathrm{OS} \bigcup_{k=1,\ldots n} \mathrm{TS}_k \tag{1}$$

To make $n + 1$ ships map to each other, the collision risk matrix M^{ξ}_{CR} and the encounter situation matrix M^{ξ}_{ES} are both constructed, each of which are $(n + 1) \times (n + 1)$ symmetric matrices and the main diagonal elements are zero, as shown in Equations (2) and (3). The matrix elements CR^b_a and ES^b_a respectively represent the collision risk of ship b relative to ship a and the encounter situation between these two ships, where M^{ξ}_{ES} is determined by M^{ξ}_{CR}:

$$M^{\xi}_{\mathrm{CR}} = \begin{bmatrix} 0 & \mathrm{CR}^{\mathrm{TS}_1}_{\mathrm{OS}} & \cdots & \mathrm{CR}^{\mathrm{TS}_k}_{\mathrm{OS}} \\ \mathrm{CR}^{OS}_{TS_1} & 0 & \cdots & CR^{\mathrm{TS}_k}_{\mathrm{TS}_1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{CR}^{\mathrm{OS}}_{\mathrm{TS}_k} & \mathrm{CR}^{\mathrm{TS}_1}_{\mathrm{TS}_k} & \cdots & 0 \end{bmatrix} \tag{2}$$

$$M^{\xi}_{\mathrm{ES}} = \begin{bmatrix} 0 & \mathrm{ES}^{\mathrm{TS}_1}_{\mathrm{OS}} & \cdots & \mathrm{ES}^{\mathrm{TS}_k}_{\mathrm{OS}} \\ \mathrm{ES}^{OS}_{TS_1} & 0 & \cdots & \mathrm{ES}^{\mathrm{TS}_k}_{\mathrm{TS}_1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{ES}^{\mathrm{OS}}_{\mathrm{TS}_k} & \mathrm{ES}^{\mathrm{TS}_1}_{\mathrm{TS}_k} & \cdots & 0 \end{bmatrix} \tag{3}$$

For the element CR^b_a, there are many ways to calculate the collision risk between ships (Szlapczynski and Szlapczynska, 2017; Chen et al., 2019). The most widely used methods are still based on the distance at closest point of approach (DCPA; unit, nautical miles) and the time to closest point of approach (TCPA; unit, minutes). This set of spatiotemporal parameters can objectively represent the risk and urgency of collision between two ships, so this paper calculates CR^b_a based on these two index values.

For DCPA, what needs to be explained here is that the value range of the original calculation result DCPA^* is equal to $(-\infty, +\infty)$. The following DCPA is the result of taking the absolute value of DCPA^*.

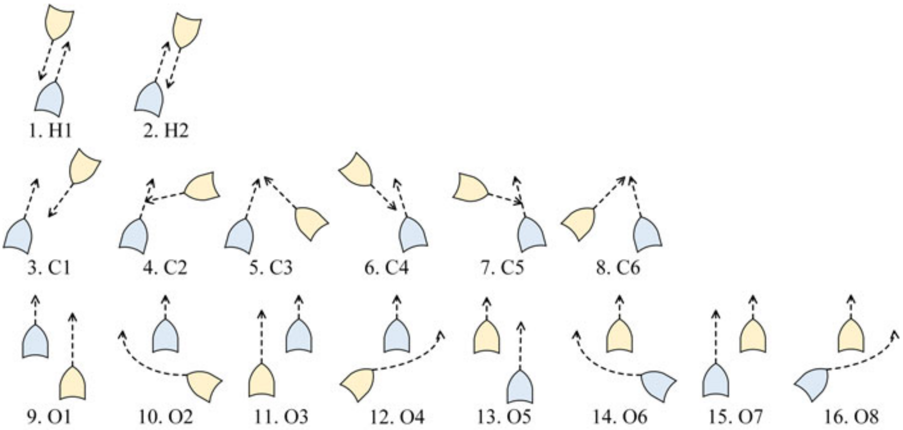


Figure 2. *The division results of 16 encounter situations.*

For DCPA*, its positive and negative values have different meanings: if the TS is on the left side of the OS, when the TS passes the bow of the OS, $\mathrm{DCPA}^* < 0$ and when passing the stern of the OS, $\mathrm{DCPA}^* > 0$; if the TS is on the right side of the OS, when the TS passes the bow of the OS, $\mathrm{DCPA}^* < 0$ and when passing the stern of the OS, $\mathrm{DCPA}^* > 0$.

This paper defines that there is no risk when $\mathrm{DCPA} > 0.9$, $\mathrm{TCPA} > 20$ or $\mathrm{TCPA} \leq 0$. In addition to this condition, the time risk function $f(\mathrm{TCPA})$ and the space risk function $f(\mathrm{DCPA})$ are constructed, as respectively shown in Equations (4) and (5). The calculation results of collision risk between two ships are obtained by weighting, as shown in Equation (6), where $\mathrm{CR}_a^b \in [0, 1]$.

$$f(\mathrm{TCPA}) = \begin{cases} 1 & \mathrm{TCPA} \leq 12 \\ \left(\dfrac{20 - \mathrm{TCPA}}{20 - 12}\right)^2 & 12 < \mathrm{TCPA} \leq 20 \\ 0 & \mathrm{TCPA} > 20 \end{cases} \tag{4}$$

$$f(\mathrm{DCPA}) = \begin{cases} 1 & \mathrm{DCPA} \leq 0.5 \\ \dfrac{1}{2} - \dfrac{1}{2}\sin\left[\dfrac{\pi}{0.9 - 0.5}\left(\mathrm{DCPA} - \dfrac{0.9 + 0.5}{2}\right)\right] & 0.5 < \mathrm{DCPA} \leq 0.9 \\ 0 & \mathrm{DCPA} > 0.9 \end{cases} \tag{5}$$

$$\mathrm{CR}_a^b = 0.6 * f(\mathrm{DCPA}) + 0.4 * f(\mathrm{TCPA}) \tag{6}$$

For the element ES_a^b, based on the requirements of relevant clauses from COLREGS, this paper further divides three typical encounter scenarios (head-on, overtaking and crossing) into 16 types. It can reflect the information between ships in a more detailed manner and assist in the formulation of collaborative strategies. The following scene divisions also need to satisfy two preconditions: (1) normal power-driven vessels while underway; (2) vessels in sight of each other. Refer to Figure 2 for symbols and schematic diagrams of encounter situations.

To describe different encounter situations, define the bearing of ship b relative to ship a as θ_a^b, and the relative course between the two ships is φ. Set the blue as ship a and the yellow as ship b. The descriptions on these 16 encounter situations are shown in Table 1.

As mentioned above, M_{ES}^{ξ} is decided by M_{CR}^{ξ}, so we define if the element $\mathrm{CR}_a^b > 0.5$ in M_{CR}^{ξ}, then ES_a^b can be obtained by Table 1; otherwise, $\mathrm{ES}_a^b = 0$. According to these two matrices, M_{CR}^{ξ} and M_{ES}^{ξ}, we can build a cooperative collision avoidance topological network, and it follow these rules:

(1) under scenario ξ, ships in danger of collision are reserved as nodes of the cooperative network;
(2) when two ships are in danger of collision, use an edge to connect these two nodes;

Table 1. *Definition of different encounter situations.*

Definition	Description	Role
H1(Head on): port to port.	$\theta_a^b \in [345°, 360°]$ and $\varphi \in [165°, 195°]$	Give way
H2(Head on): starboard to starboard.	$\theta_a^b \in (0°, 15°]$ and $\varphi \in [165°, 195°]$	Give way
C1(Crossing): starboard side with small angle.	$\theta_a^b \in (15°, 22.5°]$ and $\theta_b^a \in (247.5°, 360°]$	Give way
C2(Crossing): starboard side with normal angle.	$\theta_a^b \in (22.5°, 67.5°]$ and $\theta_b^a \in (247.5°, 360°]$	Give way
C3(Crossing): starboard side with large angle.	$\theta_a^b \in (67.5°, 112.5°]$ and $\theta_b^a \in (247.5°, 360°]$	Give way
C4(Crossing): port side with small angle.	$\theta_a^b \in (337.5°, 345°]$ and $\theta_b^a \in (0°, 112.5°]$	Stand on
C5(Crossing): port side with normal angle.	$\theta_a^b \in (292.5°, 337.5°]$ and $\theta_b^a \in (0°, 112.5°]$	Stand on
C6(Crossing): port side with large angle.	$\theta_a^b \in (247.5°, 292.5°]$ and $\theta_b^a \in (0°, 112.5°]$	Stand on
O1(Overtaken): *b* is on the starboard side of *a* and overtaking *a* from starboard side.	$\theta_a^b \in (112.5°, 180°]$ and $\text{TCPA} > 0\&\text{DCPA}^* > 0$	Stand on
O2(Overtaken): *b* is on the starboard side of *a* and overtaking *a* from port side.	$\theta_a^b \in (112.5°, 180°]$ and $\text{TCPA} > 0\&\text{DCPA}^* \leq 0$	Stand on
O3(Overtaken): *b* is on the port side of *a* and overtaking *a* from port side.	$\theta_a^b \in (180°, 247.5°]$ and $\text{TCPA} > 0\&\text{DCPA}^* \leq 0$	Stand on
O4(Overtaken): *b* is on the port side of *a* and overtaking *a* from starboard side.	$\theta_a^b \in (180°, 247.5°]$ and $\text{TCPA} > 0\&\text{DCPA}^* > 0$	Stand on
O5(Overtaking): *a* is on the starboard side of *b* and overtaking *b* from starboard side.	$\theta_b^a \in (112.5°, 180°]$ and $\text{TCPA} > 0\&\text{DCPA}^* > 0$	Give way
O6(Overtaking): *a* is on the starboard side of *b* and overtaking *b* from port side.	$\theta_b^a \in (112.5°, 180°]$ and $\text{TCPA} > 0\&\text{DCPA}^* \leq 0$	Give way
O7(Overtaking): *a* is on the port side of *b* and overtaking *b* from port side.	$\theta_b^a \in (180°, 247.5°]$ and $\text{TCPA} > 0\&\text{DCPA}^* \leq 0$	Give way
O8(Overtaking): *a* is on the port side of *b* and overtaking *b* from starboard side.	$\theta_b^a \in (180°, 247.5°]$ and $\text{TCPA} > 0\&\text{DCPA}^* > 0$	Give way

(3) the connecting edge is directional and stores information about associated ship *a* and *b*, including CR_a^b and ES_a^b.

According to the above methods, this paper gives an example based on one multi-ship encounter scenario ξ^a, as shown in Figures 3(a) and 3(b). It should be noted that although there is no direct connection between two ships in the network $\text{CR}_a^b = 0$, since they have a common connection node, it is considered that there is an indirect connection between them, as shown in Figure 3, TS-2 and TS-3, they use the OS as the relay node.

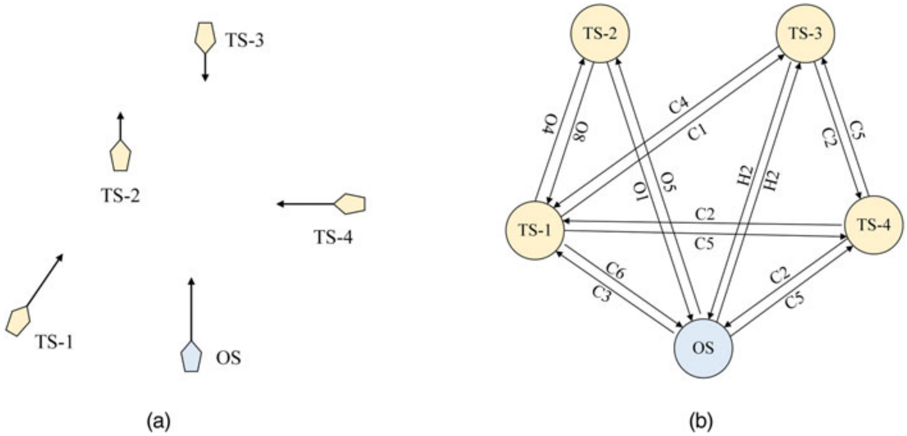


Figure 3. *A construction case for collaborative topological network. (a) Multi-ship encounter scenario ξ^a. (b) Collaborative network under scenario ξ^a.*

2.2. Multi-ship cooperative game model

2.2.1. Description of multi-ship cooperative game

The cooperative game is an important branch of game theory, which means that in the process of the game, different players can reach a binding cooperation contract to form a coalition (Lisowski, 2012). The benefits obtained by participants should not be less than the benefits obtained by independent individuals when they did not participate in the coalition. The essence of a cooperative game is to find a way to distribute benefits, promote cooperation among different participants and improve efficiency.

Multi-ship collaborative collision avoidance under mixed scenarios can be described and modelled with reference to cooperative game theory. As mentioned in Section 1.3, due to the different levels of autonomy and decision-making logic of each ship in the mixed scenario, the key for each ship to participate in this coalition to form a synergy is that the benefits of participating in the process of collision avoidance are greater than the benefits obtained by taking actions alone. In this paper, we convert the benefit distribution method of collaborative collision avoidance into the distribution problem of collision avoidance responsibility. By rationally distributing the avoidance responsibilities of all parties involved, each ship can obtain more benefits from the coalition, and promote the participation of ships with different decision logics to participate in this coordination, thereby forming a stable coalition.

Let the cooperative game formed by multi-ship cooperative collision avoidance be denoted as $G(N,\ \mu)$. According to the collaborative network constructed in Section 2.1, ships participating in the game are nodes in the network structure, and the set of game participants is denoted as N. Let $N = \{S_1, S_2, \ldots, S_n\}$, n represents the number of ships participating in the current scenario and $\mu(N)$ is the total revenue of the grand coalition formed by this complete collaboration network. For any $P \subseteq N$, we call $P = \{S_1, S_2, \ldots, S_p\}$ a sub-coalition in N, and its corresponding sub-coalition revenue is recorded as $\mu(P)$. Let $R = \{r_1, r_2, \ldots, r_n\}$ be a solution of the cooperative game $G(N,\ \mu)$, then r_k in the solution set is the collision avoidance responsibility of ship S_k.

2.2.2. Sub-coalition separation

The benefit distribution of each ship in coalition N is related to the benefit of each ship in the participating sub-coalition P. Therefore, it is necessary to divide the cooperative network into sub-coalitions to clarify which sub-coalitions each ship is in. For n ships participating in the collaboration, the dimension interval of its sub-coalition is $[1, n]$, any node is directly or indirectly connected by connecting edges, and these nodes are considered to form a coalition. The sub-coalition is obtained by dividing the major coalition, and the connection line retains CR_a^b and ES_a^b between a and b.

Taking the collaborative network in Section 2.1 as an example, the major coalition $N = 5$, so the sub-coalition dimension interval is $[1, 5]$. The results are as follows:

one-dimensional coalition P^1: {OS}, {TS-1}, {TS-2}, {TS-3}, {TS-4};
two-dimensional coalition P^2: {OS,TS-1}, {OS,TS-2}, {OS,TS-3}, {OS,TS-4}, {TS-1,TS-2}, {TS-1,TS-3}, {TS-1,TS-4}, {TS-3,TS-4};
three-dimensional coalition P^3: {OS,TS-1,TS-2}, {OS,TS-1,TS-3}, {OS,TS-1,TS-4}, {OS,TS-2,TS-3}, {OS,TS-2,TS-4}, {OS,TS-3,TS-4}, {TS-1,TS-2,TS-3}, {TS-1,TS-2,TS-4}; {TS-1,TS-3,TS-4};
four-dimensional coalition P^4: {OS,TS-1,TS-2,TS-3}, {OS,TS-1,TS-2,TS-4}, {OS,TS-1,TS-3,TS-4}, {OS,TS-2,TS-3,TS-4};
five-dimensional coalition P^5: {OS,TS-1,TS-2,TS-3,TS-4}.

2.2.3. *Revenue function*

Since a ship taking collision avoidance actions will deviate from the original route and disturb the normal navigation state, under the premise of ensuring the safety of navigation, OOWs prefer to use a small range of instructions at a suitable time. If an agreement is reached after negotiation with other ships, the OS's collision avoidance responsibility can be allocated, so that it does not need to afford 100% of the collision avoidance obligation, which is the main way for ships to participate in the coalition to obtain benefits. In addition, reaching an agreement to form a stable collaborative coalition can also ensure that each ship will take reasonable and effective evasive actions to achieve safe passing under mixed scenarios. In this section, we will give the description of the revenue function for sub-coalitions of different dimensions.

Define the benefit of the k-th ship in the sub-coalition as $\lambda(S_k)$, then for the n-dimensional sub-coalition P^n, its revenue function is shown in Equation (7). That is, the benefit of coalition is equal to the sum of the benefit of each ship in this coalition:

$$\mu(P^n) = \sum_{k=1}^{n} \lambda(S_k) \tag{7}$$

For one-dimensional coalition P^1, since only one ship is included, it cannot gain any benefit from coalition, and the revenue function of it is $\mu(P^1) = 0$.

For two-dimensional coalition P^2, suppose a two-dimensional coalition $\{s, t\}$ includes ship s and ship t, then there is a collision risk CR_s^t and encounter situations ES_s^t and ES_t^s obtained from Table 1. For a typical two-ship coalition, this paper defines that the benefit λ obtained by one ship comes from the collision risk CR_s^t that the other ship can share. This is because if a ship does not participate in coalition, since it does not know the intentions and actions of the other ship, in theory, it will have to bear all the obligation to clear the current collision risk. According to COLREGS, we can divide a two-dimensional coalition $\{s, t\}$ into the give-way and stand-on ships. For a head on situation, since both ships have the obligation to take actions, each bears 50% of CR_s^t. For other situations, the give-way ship needs to undertake the collision avoidance obligation whether it participates or not, so the benefit is equal to 0. The stand-on ship can sail directly with full confidence due to the coordination of the give-way ship, so the benefit is the entire CR_s^t. To sum up, the revenue function of two-dimensional coalition is the superposition of $\lambda(s)$ and $\lambda(t)$, as shown in Equation (8):

$$\mu(P^2) = \mathrm{CR}_s^t, \quad P^2 = \{s, t\} \tag{8}$$

For multidimensional coalition P^w $(w > 2)$, due to the increase in the number of ships, evasive actions taken by ships in different encounter situations will interact with each other, so this paper follows the strong domination property of COLREGS in the cooperative game model. Set multidimensional coalition P^w as $\{k_1, k_2, \ldots, k_w\}$, then the revenue function $\lambda(k)$ of each ship k in the multi-dimensional coalition

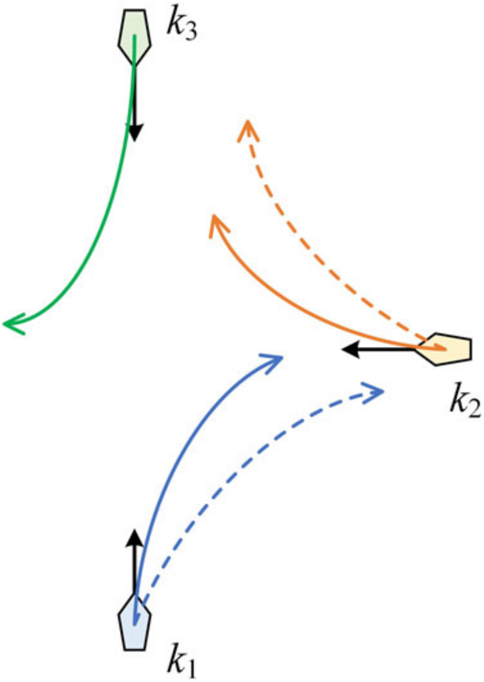


Figure 4. *Benefit to be obtained from expected evasive actions.*

is not only related to the collision risk CR shared by another ship, but also related to the expectation of the other ships' actions. The benefit of the latter mainly comes from the give-way ship defined in this mixed scenario. If the action of the stand-on ship is an assistant action (in this paper, assistant actions are related to the encounter situation between two ships: when an encounter situation belongs to head on or crossing, the same turning direction is an assistant action; when an encounter situation belongs to overtaking, the opposite turning direction is an assistant), it can be regarded as sharing collision avoidance responsibility of the give-way ship, which can reduce the range of evasive action taken by the give-way ship, so that the give-way ship can benefit from it.

Taking the three-ship coalition in Figure 4 as an example, it can be seen from Table 1 that $\mathrm{ES}_{k_1}^{k_2} = \mathrm{C2}$ and $\mathrm{ES}_{k_2}^{k_3} = \mathrm{C2}$; therefore, k_2 is a stand-on ship relative to k_1 but also a give-way ship relative to k_3. Considering $\mathrm{ES}_{k_1}^{k_3} = \mathrm{H2}$, according to COLREGS, both k_2 and k_3 need to alter course to the right side. It is an assistant action relative to k_1 and k_2, so k_1 and k_2 can turn the original dashed trajectories into solid lines, and the range of evasive actions is reduced, so k_1 and k_2 gain additional benefits.

Therefore, let $G = \{g_1, g_2, \ldots, g_v\}$ be the set of give-way ships under different encounter situations in coalition P^w, then for any one of the ships g_i, its corresponding stand-on ship is set as h_i. Take this stand-on ship as the central node to obtain all connected edge information, including encounter situation set ES_{h_i} and collision risk set CR_{h_i}.

We can index ES_{h_i} according to Table 2. Since the rules do not clearly stipulate the turning direction in an overtaking situation, the left steering is subject to the right steering. To determine whether h_i takes an assistant action can be achieved by comparing with $\mathrm{ES}_{h_i}^{g_i}$. If not, the benefit of g_i is equal to 0; if it does, the benefit of g_i in the coalition can be calculated from Equation (9):

$$\mu(g_i) = \delta * \mathrm{CR}_{h_i}^{\max} * \mathrm{CR}_{h_i}^{g_i} \tag{9}$$

Table 2. *Turning directions in different situations defined by COLREGS.*

Encounter Situation	Turning Direction
H1, H2	Right
C1, C2, C3	Right
O5, O8	Right
O6, O7	Left

Table 3. *Tuning factors under different encounter situation (give way).*

Encounter Situation	Factor(δ)
C1, O5, O7	0·3
H1, H2, C2	0·5
C3, O6, O8	0·7

Among them, δ is the tuning factor, which is determined by $\mathrm{ES}_{h_i}^{g_i}$, as shown in Table 3. A larger turning range that g_i may take suggests a higher expected benefit of h_i. In addition, $\mathrm{CR}_{h_i}^{\max}$ represents the maximum collision risk value among ships associated with g_i. A greater collision risk will result in a greater range of assistant actions that will be taken by g_i. Therefore, the total revenue of coalition P^w from taking actions by other ships is the sum of all benefits from give-way ships. In addition, let the number of connected edges (in danger of collision with each other) of coalition $\{k_1, k_2, \ldots, k_w\}$ equal m. Then the benefit of coalition P^w generated by the collision risk that can be shared by another ship under the current encounter situation is the sum of collision risks of those connection edges, so the final multi-dimensional coalition revenue function is shown in Equation (10):

$$\mu(P^w) = \sum_{j=1}^{v} \mu(g_j) + \sum_{l=1}^{m} \mathrm{CR}_l \tag{10}$$

2.2.4. *Assignment of collision avoidance responsibility*

In the previous section, the benefit calculation methods from one-dimensional to multi-dimensional coalition were introduced. In a multi-ship cooperative coalition $N = \{S_1, S_2, \ldots, S_n\}$, different participants obtain different benefits in this coalition, so it is unreasonable to evenly distribute the collision avoidance responsibility of each ship in this collaborative network when formulating a multi-ship collaborative collision avoidance strategy. The collision avoidance responsibility of each ship should be allocated proportionally according to the contribution of each ship to the total benefit μ of coalition N, and the contribution of each ship to the coalition is proportional to the distribution of benefits obtained by each ship in this coalition. Therefore, in the multi-ship cooperative collision avoidance strategy, the allocation of collision avoidance responsibility of each ship is directly related to the distribution of the coalition benefit. The collision avoidance responsibility allocation scheme that conforms to the above logic is more likely to be adopted and implemented by ships with different decision-making logic under mixed scenarios, and then promotes cooperation among multiple ships.

To calculate the solution $R = \{r_1, r_2, \ldots, r_n\}$ of a multi-ship cooperative game $G(N,\ \mu)$, this paper uses the Shapley value method (Shapley and Shubik, 1954). The most important point of this method is that it reflects the contribution of all parties in the same coalition to the overall goal of cooperation and avoids egalitarianism in the process of benefits distribution. The benefit $\mu(i)$ distributed by the i-th ship in the coalition N can be obtained by Equation (11):

$$\mu(i) = \sum_{\substack{i \in P \\ P \subseteq N}} \frac{(p-1)!(n-p)!}{n!} [\mu(P) - \mu(P - \{i\})] \tag{11}$$

According to the description in Section 2.2.1, P is a sub-coalition of N and p is the number of participants in the sub-coalition. By Equation (11), the benefit distribution of all participants in coalition N is obtained, then for the solution $R = \{r_1, r_2, \ldots, r_n\}$, the collision avoidance responsibility r_i of the i-th ship is shown in Equation (12):

$$r_i = \frac{\mu(i)}{\mu(N)} \tag{12}$$

2.3. Calculation of collaborative collision avoidance strategy

When ships do not participate in the collaborative network under a mixed scenario, it is unclear whether other ships will take evasive action. Therefore, to ensure the safety of navigation, most ships take proactive actions, and the responsibility of each ship to bear is still 100%. Due to the construction of collaborative network, ships participating in the same coalition can share collision avoidance responsibility with each other. As mentioned in Section 2.2, the more benefits obtained by participating in the coalition will mean the greater the collision avoidance responsibility is shared. In this section, according to the final result $R = \{r_1, r_2, \ldots, r_n\}$ of the cooperative game model, we use the GRVO method to calculate the final strategy for multi-ship collaborative collision avoidance under mixed scenarios, and the strategy form is the steering angle of each ship.

For any ship S_i in the coalition $N = \{S_1, S_2, \ldots, S_n\}$, with this ship as the central node, we can obtain the set of ships in different encounter situations connected to it as $D = \{d_1, d_2, \ldots, d_m\}$, and also the set of encounter situations ES_{S_i}. For any ship d_j in set D, the velocity obstacle (VO) (Van den Berg et al., 2008) for S_i induced by d_j is the set of velocities that, if chosen from, will eventually lead to a dangerous situation between two ships. Let C represent the ship position, then $\mathrm{RC} = C_{d_j} - C_{S_i}$ represents the relative position between these two ships, and let V represent the ship speed, then $\mathrm{RV} = V_{S_i} - V_{d_j}$ represents the relative speed between these two ships. Now define a ray γ that starts from the RC point and launches in the direction of RV, then the position of this ray after time t is shown in Equation (13):

$$\gamma(\mathrm{RC,RV}) = \{\mathrm{RC} + \mathrm{RV} * t \mid t \geq 0\} \tag{13}$$

Define the safe encounter distance SD between two ships to be positively correlated with ship distance $|\mathrm{RC}|$, as shown in Equation (14), units are in nautical miles. Then use the symbol ψ to represent the circular area with d_j as the centre and SD as the radius. Therefore, the velocity obstacle $\mathrm{VO}_{S_i|d_j}$ for S_i induced by d_j can be expressed as Equation (15):

$$\mathrm{SD} = 0.2 * |\mathrm{RC}|, \quad \mathrm{SD}_{\max} = 1, \quad \mathrm{SD}_{\min} = 0.5 \tag{14}$$

$$\mathrm{VO}_{S_i|d_j}(V_{d_j}) = \{V_{S_i} \mid \gamma(\mathrm{RC,RV}) \cap \psi \neq \emptyset\} \tag{15}$$

The definition of $\mathrm{VO}_{S_i|d_j}$ is based on the fact that ship S_i bears 100% of the collision avoidance responsibility relative to d_j. In other words, S_i takes evasive action alone to ensure that these two ships pass at a safe distance SD. However, in a multi-ship collaborative network under a mixed scenario, each ship is assigned with different collision avoidance responsibility according to the result $R = \{r_1, r_2, \ldots, r_n\}$ of the cooperative game. Let r_{S_i} and r_{d_j} be the collision avoidance responsibility of S_i and d_j assigned in a collaborative network, respectively, then the relative responsibility of S_i relative to

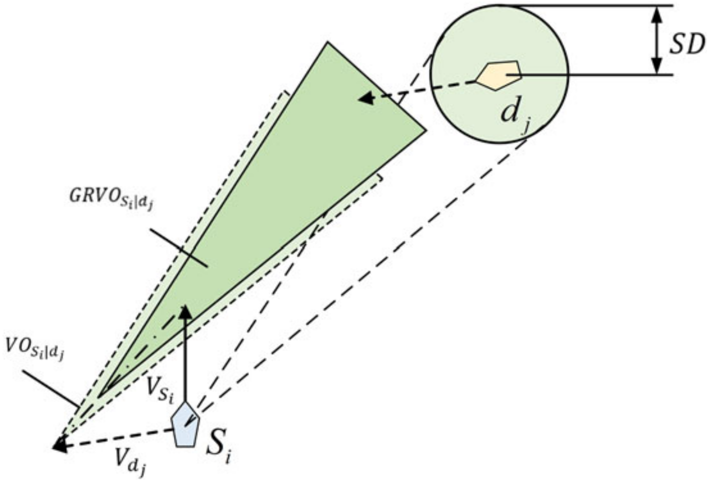


Figure 5. *Generalised reciprocal velocity obstacle.*

d_j can be calculated by Equation (16):

$$r^*_{S_i} = \frac{r_{Si}}{r_{Si} + r_{dj}} \tag{16}$$

Therefore, the original velocity obstacle $\mathrm{VO}_{S_i|d_j}$ can be updated to $\mathrm{GRVO}_{S_i|d_j}$ based on the definition of GRVO. Let the current velocity of S_i be $V^*_{S_i}$, then $\mathrm{GRVO}_{S_i|d_j}$ can be expressed as Equation (17), and the schematic is shown in Figure 5 (with a responsibility of 50%):

$$\mathrm{GRVO}_{S_i|d_j} = \left\{ V^*_{S_i} \mid \frac{1}{r^*_{S_i}} V^*_{S_i} + \left(1 - \frac{1}{r^*_{S_i}}\right) V_{S_i} \in \mathrm{VO}_{S_i|d_j}(V_{d_j}) \right\} \tag{17}$$

In addition, when situation $\mathrm{ES}^{d_j}_{S_i}$ meets the conditions listed in Table 2, $V^*_{S_i}$ will also be constrained by the turning direction. Set the turning direction constraint imposed by d_j on S_i to be σ^{d_j}, then the functions for right turning constraint $\sigma^{d_j}_r$ and left turning constraint $\sigma^{d_j}_l$ can be shown in Equation (18). Here, '×' represents the vector cross product and φ represents the relative course.

$$\begin{cases} \sigma^{d_j}_r = \{V^*_{S_i} \mid (\mathrm{RP} \times \varphi^{d_j}_{S_i})_z < 0\} \\ \sigma^{d_j}_l = \{V^*_{S_i} \mid (\mathrm{RP} \times \varphi^{d_j}_{S_i})_z > 0\} \end{cases} \tag{18}$$

Therefore, for any ship d_j in set D, S_i can provide the relative velocity obstacle area $\mathrm{GRVO}_{S_i|d_j}$ and turning constraint σ^{d_j}. Let the velocity vector corresponding to S_i at different turning angles ε be $V^{\varepsilon^*}_{S_i}$, then the initial collision avoidance decision ε_{S_i} of ship S_i in the cooperative collision avoidance coalition N can be calculated by Equation (19):

$$\varepsilon_{S_i} = \min \left\{ V^{\varepsilon^*}_{S_i} \mid V^{\varepsilon^*}_{S_i} \notin \sum_{j=1}^{m} (\mathrm{GRVO}_{S_i|d_j} \cup \sigma^{d_j}) \right\} \tag{19}$$

The initial decision $\varepsilon_{S_i}$of S_i in coalition N can meet the requirements in most scenarios, considering that the definition of Table 2 above is in accordance with the requirement of 'left turning obeys right turning'. So, for the decision ε_{S_i}, if ship d_j is regarded as the overtaken ship, and the decision of S_i relative to this ship under collision avoidance responsibility $r^*_{S_i}$ is to turn right, then the assistant action that d_j is expected to share is to turn left. However, the final decision of d_j may be a right turn in the

Table 4. *Initial state parameters of each ship in Scenario I.*

Ship Name	Ship Position (nm)	Ship Course (degree)	Ship Speed (kn)
Ship1	(0 · 3,−2)	0	15
Ship2	(−0 · 1,2 · 5)	185	10
Ship3	(3 · 2,0 · 2)	265	15

Table 5. *Collision risk matrix of Scenario I.*

	Ship1	Ship2	Ship3
Ship1	0	0 · 97	0 · 81
Ship2	0 · 97	0	0 · 78
Ship3	0 · 81	0 · 78	0

Table 6. *Encounter situation matrix of Scenario I.*

	Ship1	Ship2	Ship3
Ship1	0	H1	C2
Ship2	H1	0	C5
Ship3	C5	C2	0

global situation. Therefore, for each ship d_o^j in the subset D_o formed by the overtaken ships from set D, it is necessary to review the initial decision ε_{S_i}. If none of ε_{S_i} is located in each ship's velocity obstacle area $\mathrm{GRVO}_{S_i|d_o^j}$ in the set D_o, then ε_{S_i} is feasible; if not, let the new velocity be $V_{d_j}^*$, which corresponds to the decision of ship d_o^j in the coalition, then calculate the new velocity obstacle area $\mathrm{GRVO}_{S_i|d_j}$ and get the updated final decision O_{S_i}.

In summary, for the collaborative collision avoidance coalition $N = \{S_1, S_2, \ldots, S_n\}$ under a mixed scenario, the final solution of the cooperative collision avoidance strategy is obtained as $O = \{O_{S_1}, O_{S_2}, \ldots, O_{S_n}\}$.

3. Case study

In this section, we designed two scenarios: one is a three-ship encounter situation and the second is a five-ship encounter situation. We tested the above models in a simulation environment to verify the effectiveness of multi-ship cooperative collision avoidance strategies.

3.1. Scenario I

The initial parameters of each ship under this scenario are shown in Table 4, where the ship position is a relative coordinate with $(0, 0)$ as the centre point. According to the collaborative network construction method proposed in Section 2.1, the collision risk matrix and the encounter situation matrix among these three ships are shown in Tables 5 and 6, respectively. According to the above information, we can get a topological network of cooperative collision avoidance between ships under this scenario, as shown in Figure 6. It can be seen that these three ships in this scenario are all connected to each other, and the decision of any ship will have an impact on the other ships.

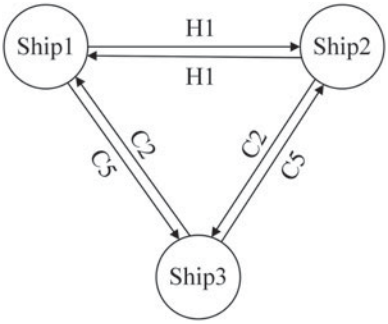


Figure 6. A collaborative topology network for Scenario I.

Table 7. Sub-coalitions of Scenario I and their benefits.

Dimension	Sub-coalition Name	Revenue
One	{Ship1}, {Ship2}, {Ship3}	0
Two	{Ship1, Ship2}	0·97
	{Ship1, Ship3}	0·81
	{Ship2, Ship3}	0·78
Three	{Ship1, Ship2, Ship3}	2·90

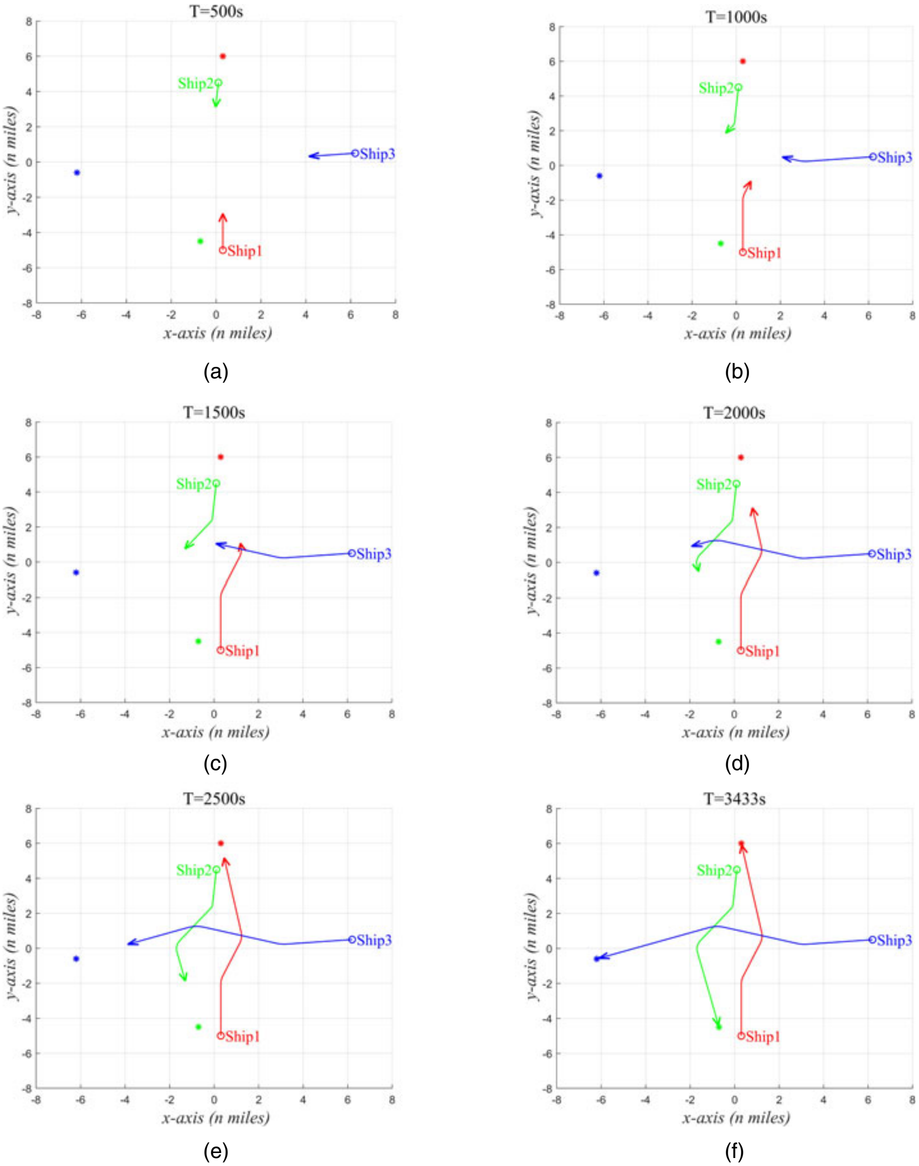
Table 8. Collision avoidance responsibility and collaborative decision for each ship under Scenario I.

Ship Name	Responsibility	Collaborative Strategy (degree)
Ship1	34·2%	22·2
Ship2	33·9%	31·9
Ship3	31·9%	20·8

According to this network, we can get the sub-coalitions with different dimensions and their benefits, as shown in Table 7. At the same time, according to the Shapley value method, the allocation ratio of collision avoidance responsibility of each ship under this scenario and the final collaborative decision of each ship can be obtained, and the results are shown in Table 8.

We assume that each ship forms a cooperative network at the position in Table 4, and the global collision avoidance responsibility assigned to each ship under this mixed scenario also reaches an agreement at this moment, that is, all three ships will take evasive actions at these coordinates in Table 4 at the same time. The final results of the simulation verification of this model in the first scenario are shown in Figure 7(a)–7(f). Figure 7 records the whole process of each ship's collision avoidance decision and the trajectory of each ship under Scenario I. The starting point of each ship is set at the position 720 s before the coordinates in Table 4, and the end point of each ship is a point on the extension line of the starting point of each ship along the ship course. To reflect the ship's manoeuvrability characteristics, we set the steering rate of each ship to 2°/10 s during the whole simulation test. In addition, we have also simplified the strategy for resuming voyages after each ship has finished evasive action, that is, if any ship meets the condition of TCPA < 0 with other ships that have been in danger of collision, then this ship ends evasion and navigates to the destination (returns to the original route). The DCPA values relative to each other when these ships take evasive action are shown in Table 9.

In addition, the relative distances with other ships during the whole process are shown in Figure 8(a)–8(c). It can be seen from the figure that although each ship imposes a steering rate, the relative distance

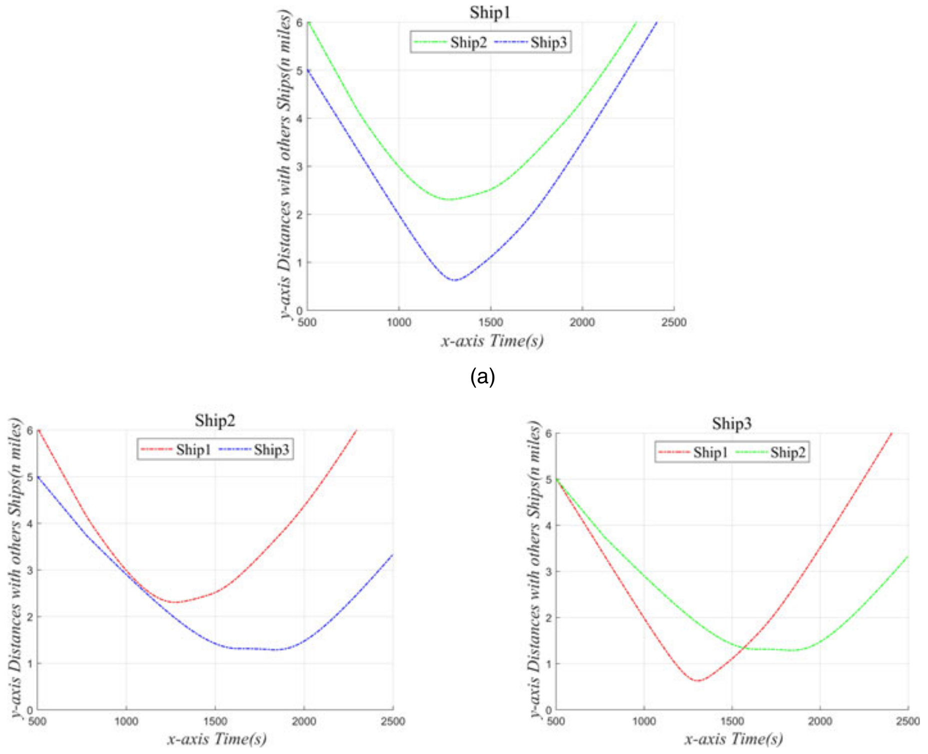


(a) (b) (c) (d) (e) (f)

Figure 7. *Collision avoidance trajectory of each ship under Scenario I. (a) T = 500 s. (b) T = 1000 s. (c) T = 1500 s. (d) T = 2000 s. (e) T = 2500 s. (f) T = 3433 s (Reach Destination).*

Table 9. *DCPA relative to other ships under Scenario I.*

	Ship1	Ship2	Ship3
Ship1	0	0 · 56	0 · 65
Ship2	0 · 56	0	0 · 23
Ship3	0 · 65	0 · 23	0



(a)

(b)

(c)

Figure 8. *Change of relative distance between ships under Scenario I. (a) Ship1. (b) Ship2. (c) Ship3.*

Table 10. *Initial state parameters of each ship in Scenario II.*

Ship Name	Ship Position (nm)	Ship Course (degree)	Ship Speed (kn)
Ship1	(1,–3)	5	16
Ship2	(–1,2 · 5)	165	14
Ship3	(4,0)	290	13
Ship4	(–0 · 5,0)	40	8
Ship5	(–3 · 5,–1)	60	18

between these ships is within the range of the safe encounter distance, which can improve the collision avoidance efficiency and effectiveness.

3.2. Scenario II

Scenario II is a more complex mixed situation, including a total of 5 ships, and the initial state parameters of each ship are shown in Table 10. The collision risk matrix and the encounter situation matrix calculated by this model, according to the information in Table 10, are shown in Tables 11 and 12, respectively. According to the above information, the topological collaborative network formed by these ships in Scenario II can be obtained, as shown in Figure 8.

It can be seen from Figure 9, the five-ship coalition can be divided into 28 sub-coalitions according to different dimensions (one-dimensional to five-dimensional), and the benefit of each sub-coalition is shown in Table 13. According to Table 13, the global collision avoidance responsibility of each ship

Table 11. *Collision risk matrix of Scenario II.*

	Ship1	Ship2	Ship3	Ship4	Ship5
Ship1	0	0	0·81	0·61	0·61
Ship2	0	0	0	0·72	0·96
Ship3	0·81	0	0	0·73	0·69
Ship4	0·61	0·72	0·73	0	0·64
Ship5	0·61	0·96	0·69	0·64	0

Table 12. *Encounter situation matrix of Scenario II.*

	Ship1	Ship2	Ship3	Ship4	Ship5
Ship1	0	0	C2	O6	C6
Ship2	0	0	0	C1	C3
Ship3	C5	0	0	C6	C6
Ship4	O2	C4	C3	0	O4
Ship5	C3	C6	C3	O8	0

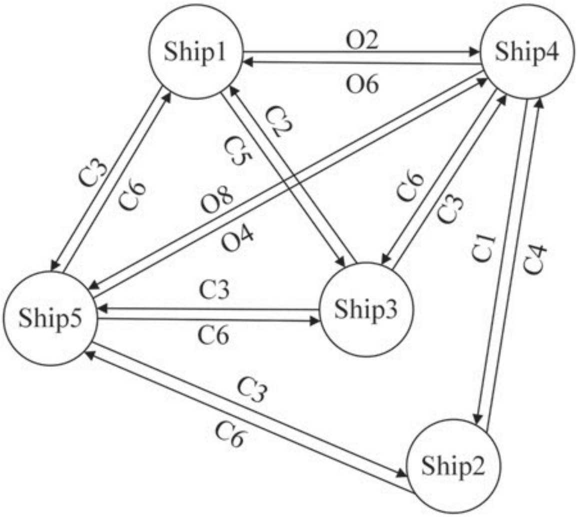


Figure 9. *A collaborative topology network for Scenario II.*

assigned by this model and the final multi-ship cooperative collision avoidance strategy under this mixed scenario can be calculated as shown in Table 14.

Consistent with the settings in Scenario I, we assume that each ship forms a cooperative network at the positions in Table 10, and at the same time, these five ships under this mixed scenario reach an agreement on the global collision avoidance responsibility assigned by this model. The final results of model simulation verification are shown in Figure 10(a)–10(f). This figure records the entire process of each ship's collision avoidance decision and the navigation trajectory. The DCPA values relative to each other when these ships take evasive action are shown in Table 15.

At the same time, we also recorded the relative distances between ships in this scenario, as shown in Figure 11(a)–11(e), respectively. According to the distance change curve, it can be known that the cooperative collision avoidance strategy generated by this model can make ships safely pass and clear.

Table 13. *Sub-coalitions of Scenario II and their benefits.*

Dimension	Sub-coalition Name	Revenue
One	{Ship1}, {Ship2}, {Ship3}, {Ship4}, {Ship5}	0
Two	{Ship1, Ship3}	0 · 81
	{Ship1, Ship4}	0 · 61
	{Ship1, Ship5}	0 · 61
	{Ship2, Ship4}	0 · 72
	{Ship2, Ship5}	0 · 96
	{Ship3, Ship4}	0 · 73
	{Ship3, Ship5}	0 · 69
	{Ship4, Ship5}	0 · 64
Three	{Ship1, Ship2, Ship5}	2 · 22
	{Ship1, Ship3, Ship5}	2 · 57
	{Ship1, Ship4, Ship5}	1 · 86
	{Ship1, Ship3, Ship4}	2 · 45
	{Ship1, Ship2, Ship4}	1 · 33
	{Ship3, Ship4, Ship5}	2 · 07
	{Ship2, Ship4, Ship5}	2 · 32
	{Ship2, Ship3, Ship4}	1 · 82
	{Ship2, Ship3, Ship5}	2 · 30
Four	{Ship1, Ship2, Ship4, Ship5}	3 · 54
	{Ship1, Ship3, Ship4, Ship5}	4 · 70
	{Ship1, Ship2, Ship3, Ship5}	4 · 07
	{Ship1, Ship2, Ship3, Ship4}	3 · 02
	{Ship2, Ship3, Ship4, Ship5}	3 · 91
Five	{Ship1, Ship2, Ship3, Ship4, Ship5}	6 · 92

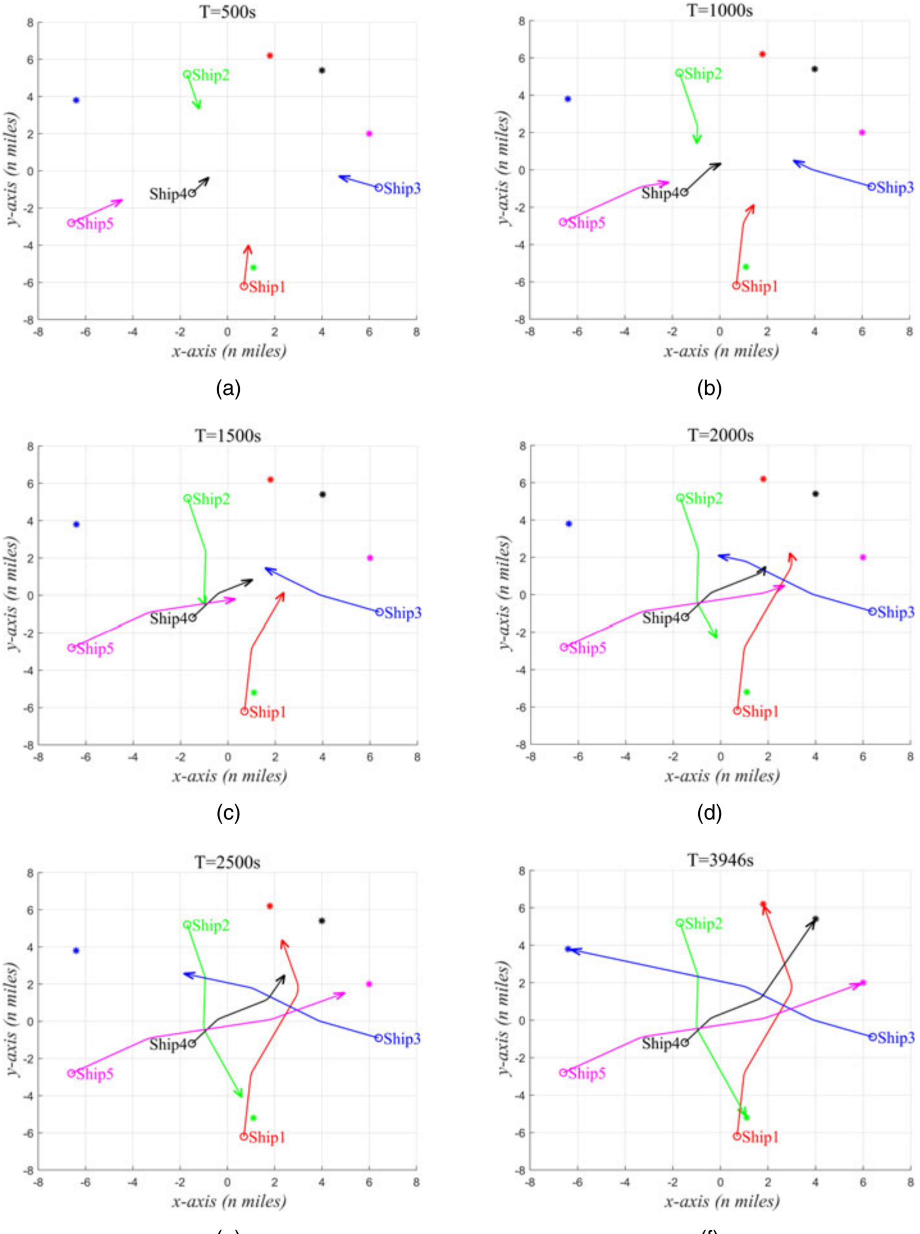
Table 14. *Collision avoidance responsibility and collaborative decision for each ship under Scenario II.*

Ship Name	Responsibility	Collaborative Strategy (degree)
Ship1	18 · 1%	19 · 7
Ship2	14 · 9%	16 · 4
Ship3	20 · 7%	12 · 1
Ship4	20 · 3%	23 · 3
Ship5	26 · 0%	19 · 1

4. Discussion

Aiming at the mixed scenario where ships with multiple autonomous levels coexist at the same time, the collaborative collision avoidance model proposed in this paper tries to solve this problem by rationally assigning the collision avoidance responsibility of each ship. Through the model verification in Section 3, this collaborative collision avoidance strategy under mixed scenarios proposed in this paper has the following advantages.

First, the most obvious benefit of the cooperative collision avoidance strategy is that the range of collision avoidance actions taken by each ship is reduced. According to the experience of collision avoidance at sea, on the premise that the evasive action can be clearly identified, a smaller range of evasive actions will mean the less deviation from the original route and the less cost generated by



(a)

(b)

(c)

(d)

(e)

(f)

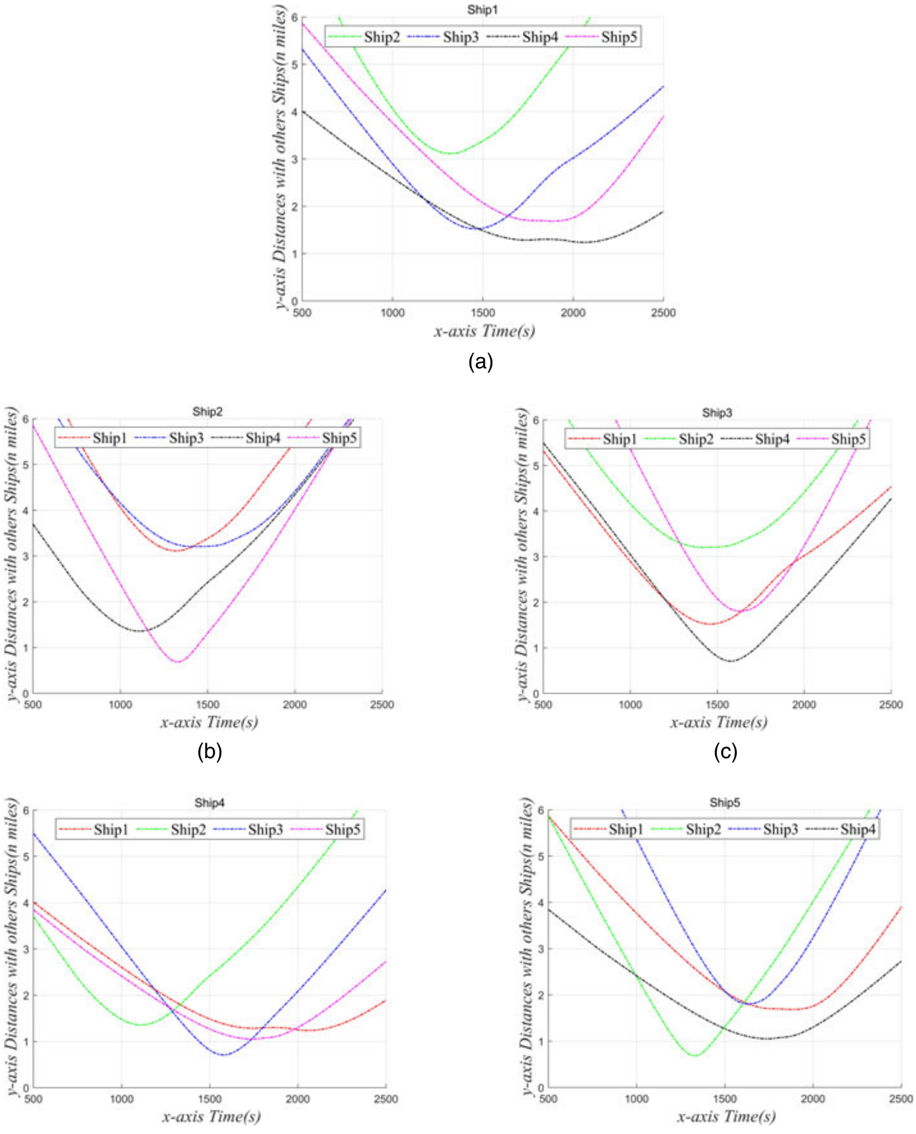
Figure 10. *Collision avoidance trajectory of each ship under Scenario II. (a) T = 500s. (b) T = 1000s. (c) T = 1500s. (d) T = 2000s. (e) T = 2500s. (f) T = 3946s (Reach Destination).*

evasive actions. Many OOWs tend to take appropriate (smaller angle) evasive decisions on the premise of ensuring safety. To illustrate this point, the velocity obstacle method is also used, and the safe encounter distance defined in Section 2.3 is also adopted. The decisions taken by each ship participating in the cooperation and not participating in the cooperation in Scenarios I and II are compared. The results are respectively shown in Tables 16 and 17. The direct reason for the reduction in the decision's range is that the ship's independent collision avoidance responsibility is shared by other ships.

Second, a collaborative strategy is a deterministic decision. Compared with the proactive collision avoidance decision-making models introduced in Section 1.2, the collaborative collision avoidance

Table 15. *DCPA relative to other ships under Scenario II.*

	Ship1	Ship2	Ship3	Ship4	Ship5
Ship1	0	1·58	0·36	0·33	0·18
Ship2	1·58	0	2·10	0·69	0·57
Ship3	0·36	2·10	0	0·43	0·23
Ship4	0·33	0·69	0·43	0	0·17
Ship5	0·18	0·57	0·23	0·17	0



(a)

(b)

(c)

(d)

(e)

Figure 11. *Change of relative distance between ships under Scenario II. (a) Ship1. (b) Ship2. (c) Ship3. (d) Ship4. (e) Ship5.*

Table 16. *Comparison of decisions before and after collaboration (Scenario I).*

Type	Ship1	Ship2	Ship3
Non-collaborative	43	62	43
Collaborative	22 · 2	31 · 9	20 · 8

Table 17. *Comparison of decisions before and after collaboration (Scenario II).*

Type	Ship1	Ship2	Ship3	Ship4	Ship5
Non-collaborative	48	45	24	47	30
Collaborative	19 · 7	16 · 4	12 · 1	23 · 3	19 · 1

strategy assigns different decisions to each ship in a multi-ship encounter situation from a global perspective, which makes the future actions of each ship in the scenario determined, reducing the potential collision risk due to the uncertainty of those behaviours taken by other ships. At the same time, this deterministic strategy makes each ship reduce the number of collision avoidance actions. From the experimental results in Section 3, each ship takes only one evasive action, which improves the efficiency of ship collision avoidance.

Third, the collaborative strategy formed through the cooperative game model is suitable for the mixed scenario involving ships with different autonomy levels. Under such a scenario, the decision-making logic of each ship is different, and it is difficult to establish objective constraints to define the collision avoidance action of each ship or to force each ship to form a coalition. However, the collision avoidance responsibility assigned to each ship through the cooperative game model can satisfy both ‘collective rationality’ and ‘individual rationality’, which can improve the rationality of responsibility assignment and encourage each ship to accept coordination to form a stable coalition.

The multi-ship collision avoidance strategy proposed in this paper provides the possibility to realise collaborative collision avoidance between ships in mixed scenarios. This strategy is essentially a centralised collaborative collision avoidance method. However, for mixed navigation scenarios where ships of different autonomy levels coexist in open waters, it is difficult to determine a centralised and coordinated cooperative control unit. Therefore, considering the practical application of this strategy in the future, the calculation of the collaborative collision avoidance strategy proposed in this paper will be based on the distributed calculation method. This strategy will aim to promote collaborative collision avoidance between ships, and as an advantageous strategy, it will become the basis for collaborative interaction between ships. The specific collaborative process is shown in Figure 12. Under the mixed scenario, one ship (Ship-1) generates a collaborative collision avoidance strategy according to this paper, which not only includes the strategy that the OS plans to adopt, but also includes the action expectations for other ships, then broadcasts the strategy to other ships in the collaborative network and the other ships will give feedback after receiving this strategy. Since this strategy is based on cooperative game theory, it will have a high probability of promoting coordination among multiple ships. This model will imitate the scene of collision avoidance coordination between OOWs through a VHF radio. At the same time, in terms of future ship cooperative data communication, the VHF data exchange system (VDES), as an enhanced and upgraded version of AIS in the field of water mobile services, will provide technical support for inter-ship collaboration under mixed scenarios.

In future research work, we will try to explore the architecture of collaborative interaction between ships based on this collaborative strategy, focusing on the interactive dynamic feedback mechanism and the optimisation theory of collaborative strategies, so as to provide new ideas for multi-ship collision avoidance under mixed scenarios.

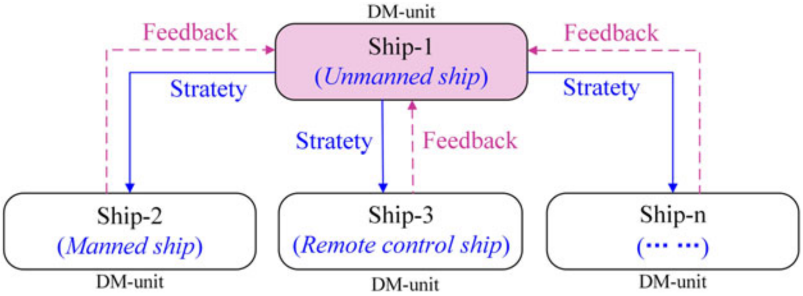


Figure 12. *Multi-ship cooperative interaction mechanism.*

5. Conclusion

With the continuous improvement of ship intelligence, the level of autonomous operation is also rising. For traditional ship collision avoidance, different OOWs can coordinate with each other through a VHF radio to achieve safe passing. For the mixed marine scenarios, where ships with different levels of autonomy coexist, the traditional coordination method is not effective, so it is necessary to study a multi-vessel collaborative collision avoidance strategy suitable for this mixed scenario. Considering the above, the collaborative objects and timings of the mixed scenario are determined first, which is by calculating a double matrix (collision risk matrix and encounter situation matrix) and forming a collaborative network. After that, according to the cooperative game theory, based on collective rationality and individual rationality, the assignment of collision avoidance responsibility of each ship under the mixed scenario is obtained, and the final collaborative strategy is calculated according to GRVO. The verification of two complex cases shows that the model proposed in this paper can effectively solve the problem of multi-vessel collaborative collision avoidance under mixed scenarios. It can enable ships with different decision-making logic to pass at a safe encounter distance, which has certain reference significance for the multi-ship collaborative collision avoidance problem under the coexistence of ships with different autonomous levels in the future.

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