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Multi-Ship Encounter Situation Identification and Analysis Based on AIS Data and Graph Complex Network Theory

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Abstract: In order to detect multi-ship encounter situations and improve the safety of navigation, this paper proposed a model which was able to mine multi-ship encounter situations from Automatic identification system (AIS) data and analyze the encounter spatial-temporal process and make collision avoidance decisions. Pairwise encounters identification results and ship motion index were combined into a ship encounter graph network which can use the complex network theory to describe the encounter spatial-temporal process. Network average degree, network average distance and network average clustering coefficient were selected. Based on the recognition results of pairwise encounter identification results, a discrete multi-ship encounter network is constructed. The process of multi-ship encounters from simple to complex to simple is mined based on the process of average network degree from 0 to 0 to obtain a continuous spatial-temporal process. The results can be used for multi-ship encounter situation awareness, multi-ship collision avoidance decision-making and channel navigation evaluation, and also provide data for machine learning. Quaternary dynamic ship domain, fuzzy logic and the weighted PageRank algorithm were used to rank the whole network risk, which is critical to "key ship collision avoidance." This method overcame the problem that the traditional collision risk evaluation method is only applicable to the difference between two ships and ship perception. The risk rank combined with the artificial potential field method was used. Compared with the traditional artificial potential field method, this method has fewer turns and a smoother trajectory.

Keywords: multi-ship encountering; navigational safety; AIS; Graph theory; COLREGS; maritime traffic

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1. Introduction

Situation awareness is critical to the officer on watch (OOW) and the maritime administration. Developing a multi-ship encounter situation automatic identification and analysis model can help them understand the situation quickly and correctly and reduce the danger of the ship-ship encounter because of misunderstanding of the current situation. According to a large number of surveys, ship collision accidents are one of the key factors affecting the safety of the shipping industry [1]. These surveys also found that the main causes of ship collision accidents were human factors, including the failure to detect the target ship in time, the misunderstanding of the intention of the target ship, and the failure to conduct safety avoidance operations in accordance with the International Regulations for Preventing Collisions at Sea (COLREGS). Collision accidents are concentrated in ports [1], bays and other areas where ships occur frequently. Since IMO (the International Maritime Organization) and IALA (the International Association of Lighthouse Authorities) put forward the concept of E-navigation, major navigation countries in the world have conducted extensive research and practice of E-navigation and achieved fruitful results, including the European Union MONALISA project, EfficienSea project, etc. One of the tasks of E-navigation is to perceive the ship's dynamics and give hints for collision avoidance. Shenzhen pilotage and navigation aid system provides a collision avoidance scheme for multiple ships based on ship AIS data and trial operation function in the intersection area of Tonggu Waterway. The ship traffic coordination and organization model applied in the compound channel of Tianjin Port also takes into account the ship conflict resolution strategy.

Ships in the situation may take uncoordinated actions to avoid collisions because of the incomplete understanding of the situation. Figures 1 and 2 show that the inconsistent understanding of the encounter situation is one of the most important reasons for collision accidents [2]. There are many reasons making it difficult to properly look out, such as the situation's complexity, poor communication quality, light signals interference and so on. COLREGS only defines the collision-avoiding principles when two ships meet. There is a lack of rules and consensuses related to the multi-ship encounter situations, and mariners can handle the ship in those situations according to a safe speed and good seamanship in COLREGS. In view of the multi-ship encounter situations, the traditional intuitive judgment and analysis can no longer meet the needs of water traffic management [3]. At present, the identification process of multi-ship encounter situations mainly depends on manual work, and the collision avoidance suggestions of multi-ship encounters mainly depend on maritime administration. Automating relevant processes is conducive to improving work efficiency and maritime traffic safety. Based on the automatic identification and analysis algorithm of the multi-ship encounter situation process, the ship encounter data can be collected and analyzed so that it can be used to guide collision avoidance to reduce collision accidents.

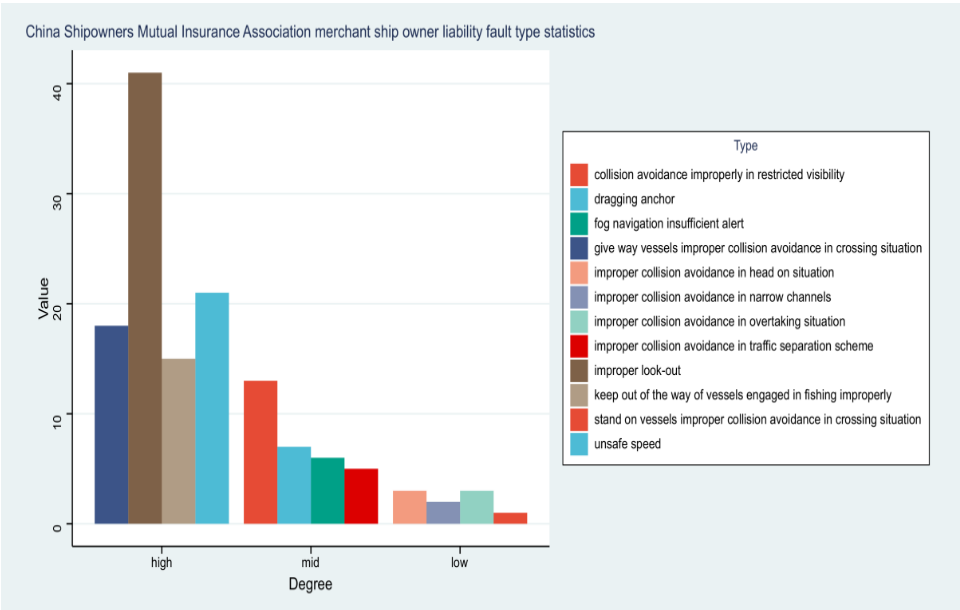


Figure 1. China Shipowners Mutual Insurance Association merchant ship owner liability fault type statistics.

It is an inevitable requirement to conduct multi-ship encounter research. The Nautilus Federation conducted [4] a questionnaire survey of 1000 shipping industry practitioners, considering that the relationship between MASS(Maritime Autonomous Surface Ships) and conventional vessels during the transitional period is one of the most important MASS safety problems. The guiding role of the COLREGS in ship collision avoidance has been profoundly rooted in the hearts of the mariners. Facing multi-ship encounter situations, mariners will subconsciously apply the COLREGS [5]. The development of MASS is gradual, and the mixed situation of manned ships and MASS [6] is inevitable. Unmanned vessels should also abide by the COLREGS, which has become the consensus of intelligent collision avoidance research of MASS.

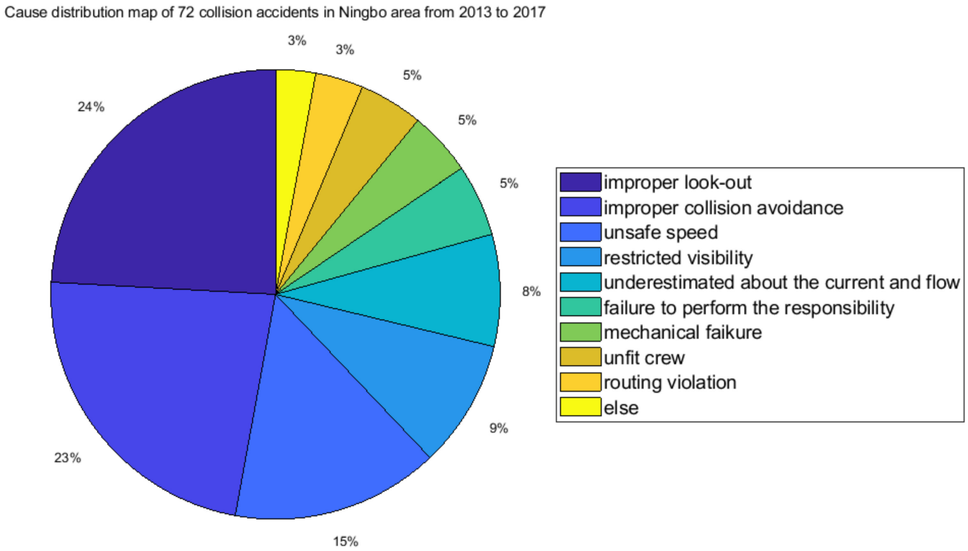


Figure 2. Cause distribution map of 72 collision accidents in the Ningbo area from 2013 to 2017.

In summary, the main contribution of this paper is developing a multiple ship encounter situations automatic identification and analysis model. Figure 3 shows the section structure diagram of this paper. The rest of this paper is organized as follows. Section 2 provides a literature review of ship encounter automatic identification models. Section 3 introduces the pairwise encounters identification method, followed by multiple ship encounter situations automatic identification and analysis model based on complex network theory in Section 4. Section 5 introduces the multiple ship coordinated collision avoidance method based on risk rank and artificial potential field. The discussion and conclusions are addressed in Section 5.

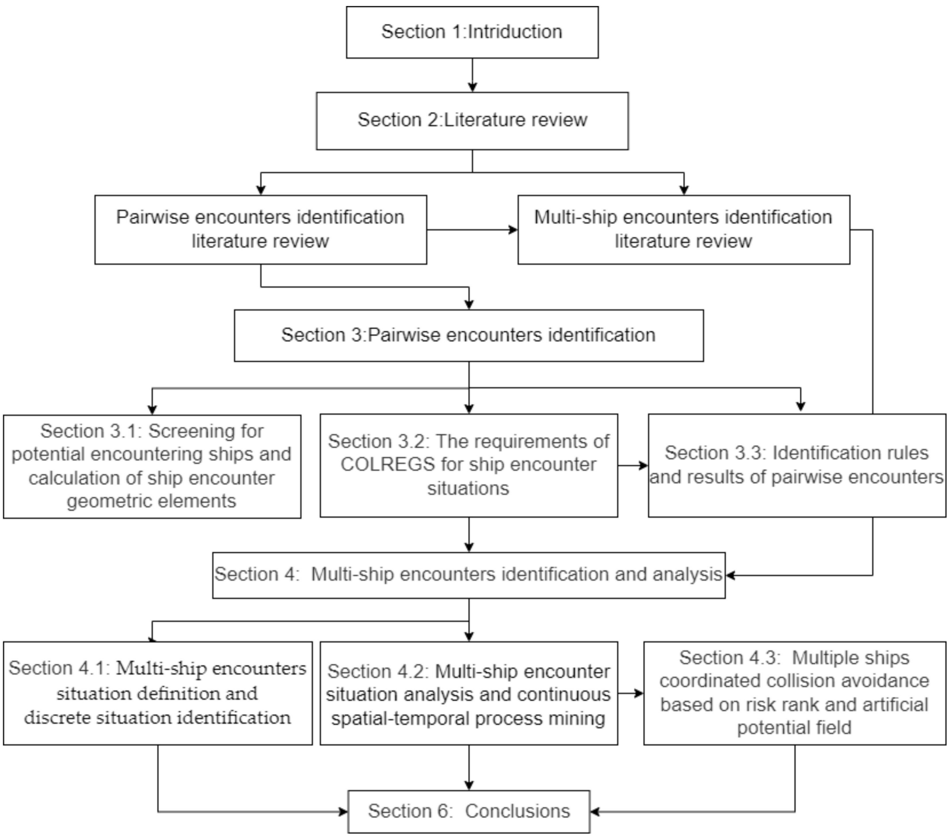


Figure 3. Section structure diagram of this paper.

2. Literature Review

The current autonomous identification study of ship encounter situations mainly focuses on the encounter between two power-driven vessels in sight of one another. These studies are based on geometric elements and COLREGS, ship domains, SVM (support vector machine), DBSCAN (Density-Based Spatial Clustering of Applications with Noise) and so on. Jiang et al. [7] calculated ship encounter geometric elements, the identification results are obtained according to the factor calculation results and COLREGS. Zhang et al. [8] constructed the fitting equation of distance, heading difference and relative speed to describe the situation and potential collision risk indicator and identified situations from the spatial perspective. Ren et al. [9] set domain boundaries to extract encounter data based on AIS data and analyzed encounter characteristics of the Waigaoqiao waterway and Yangshan warning area from four aspects: overall encounter situation, parameters of encounter ships, spatial-temporal distribution of encounter ships, and encounter state. Ma [10] et al. constructed the spatial-temporal sequence of ship encounters considering the spatial-temporal process of encounters and identified the ship encounters process based on a support vector machine. Gao et al. [11] Constructed a ship encounter azimuth map based on AIS data and support vector classification. Zhen et al. [12] calculated the ships' distance based on AIS data, and the ship encounter identification is carried out by density clustering based on distance.

The multi-ship encounter situation is characterized by high complexity and uncertainty. Through the analysis of multi-ship encounters, it can help the officers and traffic controllers understand the current situation of multi-ship encounters and also provide the ship officers with auxiliary decision-making suggestions for multi-ship collision avoidance. The way to identify the multi-ship encounter situation is similar to pairwise encounter identification but more difficult. Most of the previous research on multi-ship encounter situation mining is based on density clustering, which only considers the distance between ships and cannot fully reflect the relative relationship between ships. Previously, the analysis of multi-ship encounter situations was mostly based on simulation data, and the real multi-ship encounter situations data was not used for analysis. Wen et al. [13] quantitatively studied the complexity of regional water traffic flow and established a complexity measurement model of the water traffic flow by analyzing the structural characteristics of water traffic flow. Zhong et al. [14] evaluated the importance of ship nodes in the multi-ship network based on complex network theory. Cauteruccio [15] et al. considered degree centrality and eigenvector centrality to measure assortativity. Li et al. [16] used the ST-DBSCAN algorithm for clustering and Apriori algorithm for association analysis to mine spatial-temporal multi-ship encounter situation patterns. Hu et al. [17] mined potential adjoint patterns of target trajectory data based on a density clustering algorithm and association analysis. Zhen et al. [18] took the encounter distance of each ship under the influence of multi-feature coupling as the distance threshold of density clustering and realized real-time recognition of multi-ship encounters based on an adaptive density clustering algorithm. Table 1 shows the summary of situation identification-related works.

Gao thought [19] that when three or more vessels were on the navigation radar search area within 12 nautical miles, these vessels were in a multi-ship encounter situation. Li [20] gave a definition of multi-ship encounters based on AIS data: in the spatial-temporal AIS data, the multi-ship distances satisfy certain criteria, regardless of ship type or tonnage, whether ships have taken actions or their action effect.

Zhou [21] et al. defined the multi-ship encounter situation as where the number of ships encountered exceeds one within 12 N miles. Wu [22] et al. thought when three or more ships encountered each other, if the ship encounters all target ships at the same time or only forms a pairwise encounter and the collision avoidance actions the ship must take are limited due to the presence of other target ships, it is said that the ship is in a multi-ship encounter situation.

Table 1. Summary of situation identification-related works.

Authors' Name	Situation	Method
Gang, L.H. et al. [7]	pairwise encounter situation	metric elements and COLREGS
Zhang, W. et al. [8]	pairwise encounter situation	metric elements and COLREGS
Ren et al. [9]	pairwise encounter situation	ship domain
Ma [10]	pairwise encounter situation	support vector machine.
Gao et al. [11]	pairwise encounter situation	support vector classification
Zhen et al. [12]	pairwise encounter situation	DBSCAN
Wen et al. [13]	multi-ship encounter situation	complexity azimuth map
Li et al. [16]	multi-ship encounter situation	ST-DBSCAN
Hu et al. [17]	multi-ship encounter situation	DBSCAN
Zhen et al. [18]	multi-ship encounter situation	adaptive DBSCAN

Ni considered that [23] multi-ship collision avoidance generally refers to the situation in that multiple vessels need to take action to avoid collision in the same area. According to Wang [24], the definition of a "multi-ship encounter" is that when the ship gives way to a certain stand-on vessel, it also takes the task of giving way to other ships, or the existence of other ships makes it impossible for the ship to give way according to the COLREGS. Zheng [25] defined the multi-ship encounter as follows: in specific waters, three or more ships proceed close to each other if one ship encounters all the other target ships at the same time, or the ship only encounters one of the target ships, but its anti-collision action is confined with the existence of other target ships. Table 2 gave the different definitions of multi-ship encounter situations.

Table 2. Three kinds of multi-ship encounter situations definitions.

Distance		GAO [22], LI [23]
Distance, pairwise encounters identification results		ZHOU [24], WU [25]
Distance, uncoordinated actions to avoid collision		Ni [26], Wang [27], ZHENG [28]

The graph was used to describe and analyze the multi-ship encounter situations in this paper. A graph and a complex network theory were used to describe the complexity of the ship encounter relationship and ship motion index. The two multi-ship encounter situations coordinated collision avoidance decision methods were given: artificial potential field method based on risk rank and isomorphism of graphs. Risk rank based on quaternary dynamic ship domain, fuzzy logic and the weighted PageRank algorithm can be used in other collision avoidance methods.

3. Pairwise Encounters Identification

3.1. Screening for Potential Encountering Ships and Calculation of Ship Encounter Geometric Elements

AIS data play an important role in traffic safety [26]. AIS [27] can serve as a tool to avoid collisions and increase onboard situational awareness. In this paper, AIS data from the Zhoushan water area was used, whose longitude range was (122° E, 122.7° E) and latitude range was (29.35° N, 29.9° N). Figure 4 shows the AIS data used in the manuscript. In contrast, the identification range of ship encounters is considerably smaller than the AIS data range. Directly traversing the AIS data at the same time will lead to a large number of invalid operations, which makes the encounter identification algorithm complex.

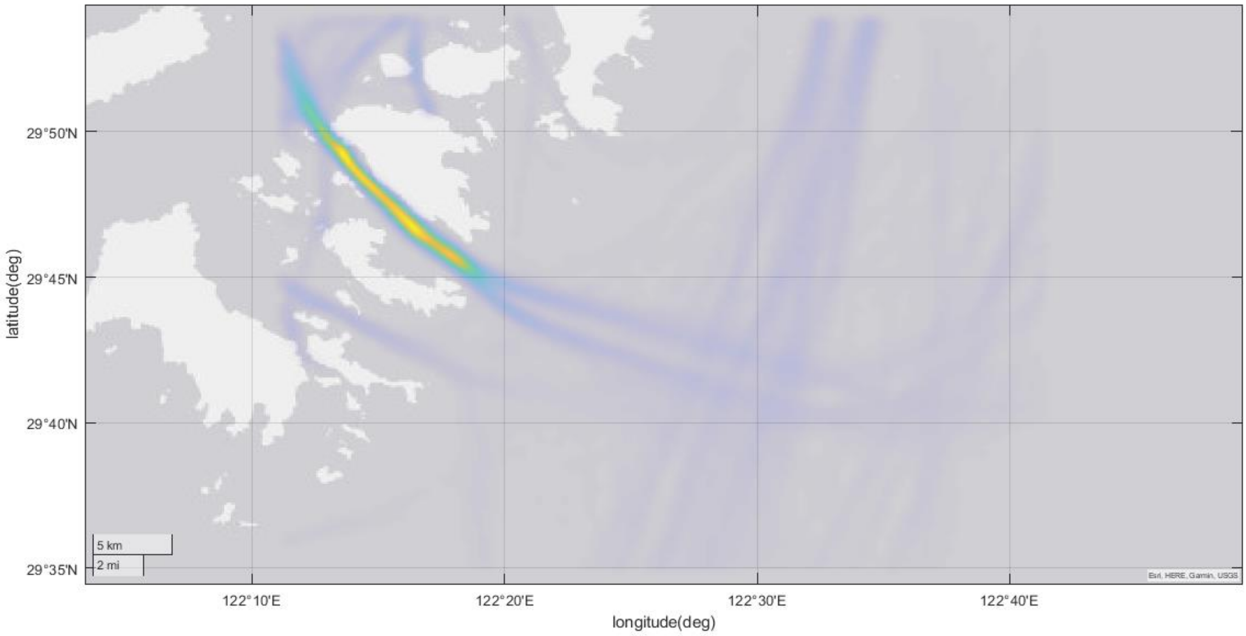


Figure 4. Zhoushan AIS data density map.

The ship encounter process could be likened to the infection and recovery of infectious disease patients, putting forward the concept of the spatial-temporal encounter of ships, and the potential encounters of two ships and multiple ships are screened based on the concept of ship spatial-temporal encounters. The latitude and longitude grid of 0.1° × 0.1° was used as the research unit. It is considered that when a ship remains in the same grid for more than 10 min, it is considered that an encounter may occur. Based on this method, the ships that may encounter are screened.

The latitude range of the two ships was (29.83° N, 29.875° N), and the longitude range was (122. 18° E, 122.22° E). The two ships stay in the same grid for more than 10 min, which demonstrates the effectiveness of this method. Those two ships are called 'spatial-temporal companions.' Figure 5 shows the head-on case based on AIS data to explain the concept of 'spatial-temporal companions'.

Due to communication and instrument reasons, data missing or errors frequently occur in the AIS data, so it is necessary to clean and interpolate the data. Multi-ship encounter situations cannot be identified because time data is not at the same time. Because the navigation elements do not change much, the data is processed by the linear interpolation method. The geometric element method is the basic method to identify the ship encounter situation. Radar plotting is the basic ability of mariners. The corresponding calculation method of ship encounter geometric elements was given.

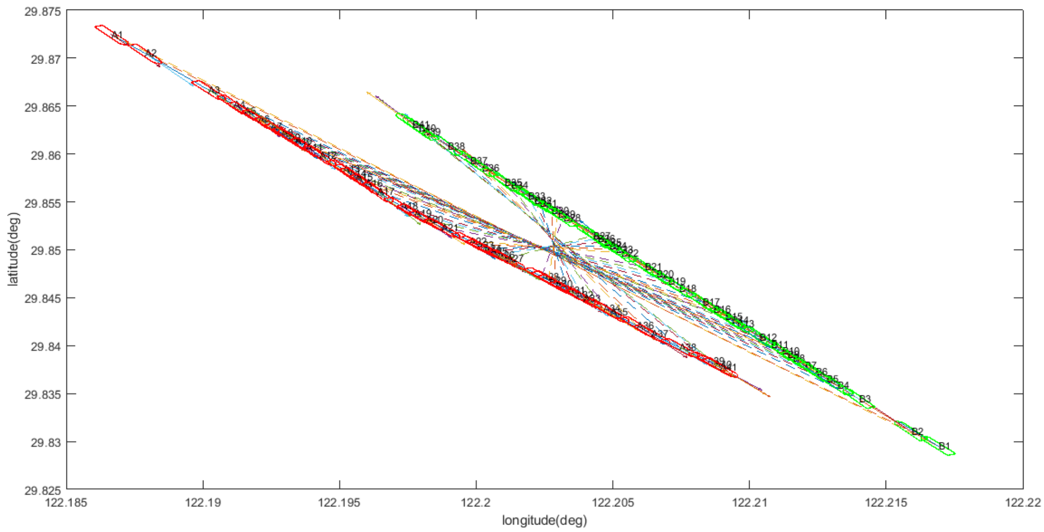


Figure 5. A head-on case based on AIS data.

The motion parameters of the ship can be obtained from the AIS data. Figure 6 shows the relationship between ship encounter geometric elements, which is the foundation of pairwise encounter identification. The latitude of the ship is LATo, the longitude is LONo, the speed is Vo, and the course is Co. The latitude of the target ship is LATT, the longitude is LONT, the speed is VT, the course is CT, and TB represents the true bearing. The relative motion parameters include DCPA(the distance to the closest point of approach), TCPA(time to the closest point of approach), the distance D between the two ships, the relative velocity RV, the course difference C, the target ship's position relative to the own ship Bo, and the ship's position relative to the target ship BT. In particular, the ship obtains the ship collision risk indicator based on the quaternary ship domain and fuzzy logic.

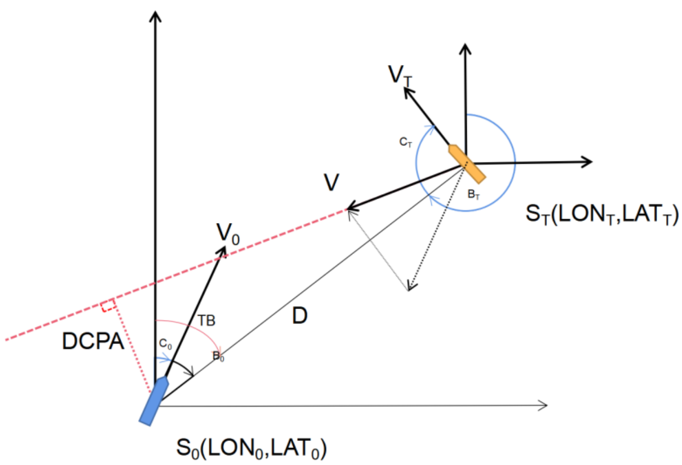


Figure 6. The relationship between ship encounter geometric elements.

3.2. The Requirements of COLREGS for Ship Encounter Situations

Figure 7 shows the types of ship encounter situations to explain COLREGS. Rule 15 of the COLREGS defines the crossing situation [28]. When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side, those two ships are in the crossing situation. The heading of the target ships 10 and 5 does not intersect with the own ship, so it is not the crossing situation. Rule 14 of the COLREGS defines the head-on situation. Target ships 7 and 8 meet the conditions of the traditional encounter identification model. When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve the risk of collision, those two ships are in a head-on situation. Since the heading of target vessel 7 does not comply with the condition of heading opposite or close to opposite as stipulated in the COLREGS, target vessel 7 does not constitute an encounter with the vessel. According to rule 14, when a vessel is in any doubt as to whether such a situation exists, she shall assume that it does exist and act accordingly, so target ships 14,15 may be deemed to be in a head-on situation. Rule 13 of the COLREGS defines the overtaking situation. A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is overtaking that at night she would be able to see only the stern light of that vessel but neither of her sidelights. Because the traditional overtaking situation identification model does not reflect the speed of the target ship, the target ship 1, 2, and 3 meet the requirements of the traditional overtaking situation identification model. However, since the speed of target ship 2 is less than the speed of its own ship, it does not constitute an overtaking situation. The distance between target ship 3 and the own ship is becoming longer, so it does not constitute an overtaking situation. Target ships 4, 11, 12 and 13 shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft the own ship beam since, according to rule 13, when a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly. Table 3 gave the common cases and special cases of the three types of ship encounter situation.

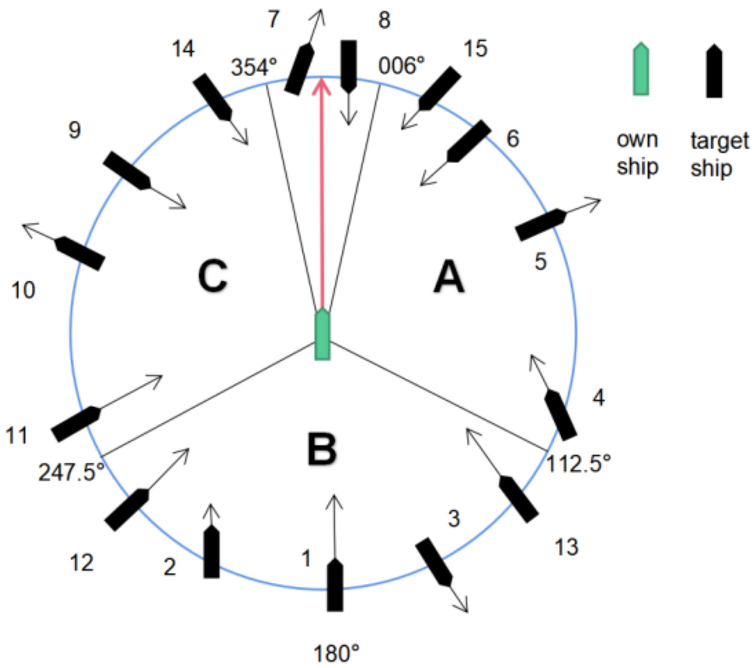


Figure 7. Types of ship encounter situations.

Table 3. Three types of ship encounter situation and their special cases.

Situation	Common Cases	Special Cases and Their Reasons
crossing	Ship 6, ship 9, ship 14, ship 15	Ship 5 and ship 10: do not intersect with their own ship
head on	ship8	Ship 7: the heading is not opposite or close to opposite their own ship
overtaking	Ship 1, ship 12, ship 13	Ship 2: the speed of target ship 2 is less than the speed of its own ship Ship 3: the distance between ship 3 and their own ship is becoming larger Ship 4, ship11: from a direction more than 22.5 degrees abaft their own ship

3.3. Identification Rules and Results of Pairwise Encounters

When two vessels are in sight of one another, there are three different types: overtaking, head-on, and crossing situations. Wu et al. [22] thought that the identification rules of pairwise encounters are as follows.

Head on:

$$\begin{cases} Q \in [0^{\circ}, 6^{\circ}] \cup [354^{\circ}, 360^{\circ}] \\ Q_t \in [0^{\circ}, 6^{\circ}] \cup [354^{\circ}, 360^{\circ}] \\ \Delta C \in [174^{\circ}, 186^{\circ}] \\ CR = 1, D \leq D_E \end{cases} \quad (1)$$

Overtaken:

$$\begin{cases} Q \in [112.5^{\circ}, 247.5^{\circ}] \\ TCPA > 0 \\ D \leq D_E \end{cases} \quad (2)$$

Overtaking:

$$\begin{cases} Q_t \in [112.5^{\circ}, 247.5^{\circ}] \\ TCPA > 0 \\ D \leq D_E \end{cases} \quad (3)$$

Crossing:

$$\begin{cases} Q \in [6, 112.5] \cup [247.5, 354] \\ CR = 1 \\ D \leq D_E \end{cases} \quad (4)$$

Q is the relative bearing of the target ship relative to the own ship; Qt is the relative bearing of the own ship relative to the target ship; ΔC is the heading intersection angle between the target ship and the own ship; CR is the collision risk indicator of two ships; D is the distance between two ships; TCPA is the latest meeting time of two ships; DE is the distance between two ships when the identification rules begin to apply. The distance threshold value for overtaking is 3 and 6 nautical miles for head-on and crossing situations, respectively.

The ship encounter is a continuous process, and the original identification rules ignored that. For example, when two ships are in a head-on situation but not past and clear, they could be identified as the crossing situation because of relative bearing. The identification rules have been amended, and the past and clear concepts in the COLREGS must be considered. Taking distance, collision risk indicator and TCPA as exit conditions, when the distance between two ships is greater than 3 nautical miles, there is no collision risk, and the two ships are moving apart; they are past and clear.

The relative bearing should also be considered [11]. If the above factors are satisfied, it is considered that the two ships have passed and cleared. Table 4 gave the relative bearing standards of the pass and clear.

Table 4. Relative bearing standards.

Situation	Left-to-Left	Right-to-Right
Head on situation	$\begin{cases} 180^{\circ} \leq B_O \leq 260^{\circ} \\ 180^{\circ} \leq B_T \leq 260^{\circ} \end{cases}$	$\begin{cases} 100^{\circ} \leq B_O \leq 180^{\circ} \\ 100^{\circ} \leq B_T \leq 180^{\circ} \end{cases}$
	overtaken from the right side	overtaken from the left side
Overtaken situation	$\begin{cases} 0^{\circ} \leq B_O \leq 80^{\circ} \\ 180^{\circ} \leq B_T \leq 260^{\circ} \end{cases}$	$\begin{cases} 280^{\circ} \leq B_O \leq 360^{\circ} \\ 100^{\circ} \leq B_T \leq 180^{\circ} \end{cases}$
	crossing the stern	crossing the bow
Crossing situation	$\begin{cases} 100^{\circ} \leq B_O \leq 180^{\circ} \\ 10^{\circ} \leq B_T \leq 90^{\circ} \end{cases}$	$\begin{cases} 270^{\circ} \leq B_O \leq 350^{\circ} \\ 180^{\circ} \leq B_T \leq 260^{\circ} \end{cases}$

Three groups of examples are given respectively for head-on, overtaking, and crossing situations. A represents the own ship, B represents the target ship, and the number represents the time. Figure 8 proves the effectiveness of the method.

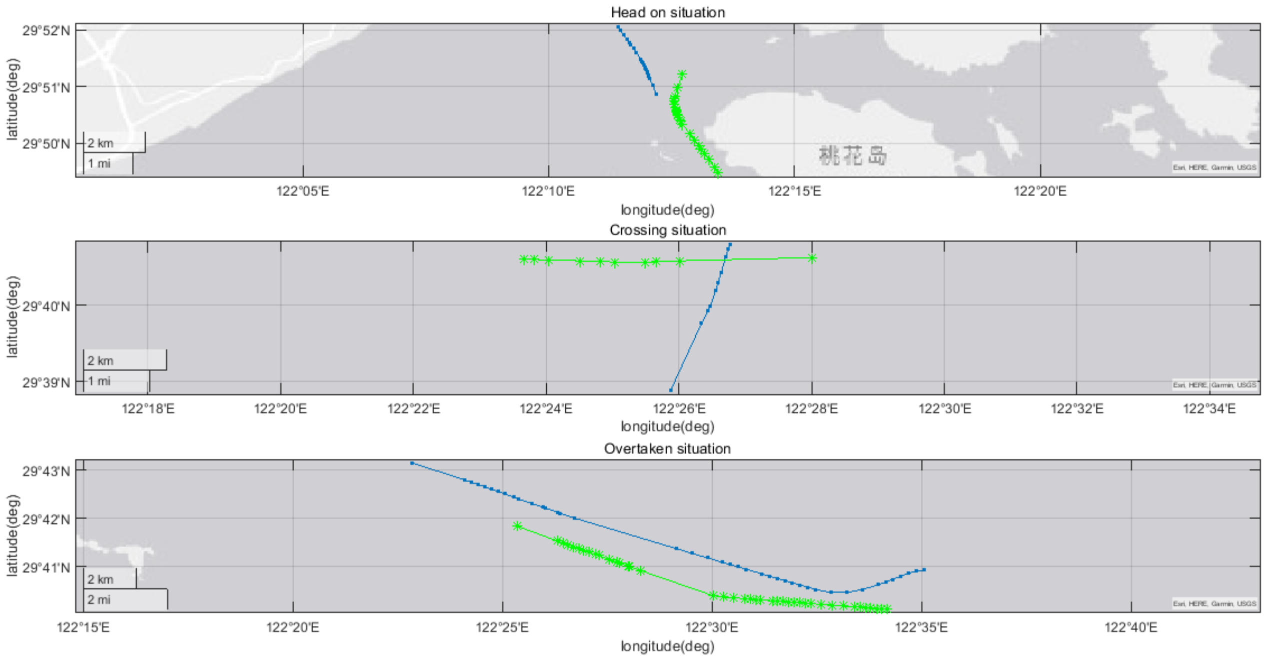


Figure 8. Identification results of pairwise encounters.

4. Multi-Ship Encounter Identification and Analysis

4.1. Multi-Ship Encounters Situation Definition and Discrete Situation Identification

According to the discussion of the above scholars, the identification of multi-ship encounters should conform to the navigation practice and identification results of pairwise encounters according to the COLREGS. The identification result should be considered as a network and can analyze the ship handling. Cauteruccio [15] et al. defined a support network that was composed of node and edge so that it could be analyzed.

Encounter relationships are relative relationships between vessels, so the graph structure is chosen to store and represent multi-ship encounter situations. The key to generating a vessel encounter graph is to define its edges and points. In this paper, it is believed that the point in the multi-ship encounter situation represents the ship's attributes, including the ship's longitude, latitude and heading speed at that moment and that the edge represents the relative relationship, including the relative motion parameters the identification result of the pairwise encounter. Figure 9 shows the identification flow of multiple ship encounters.

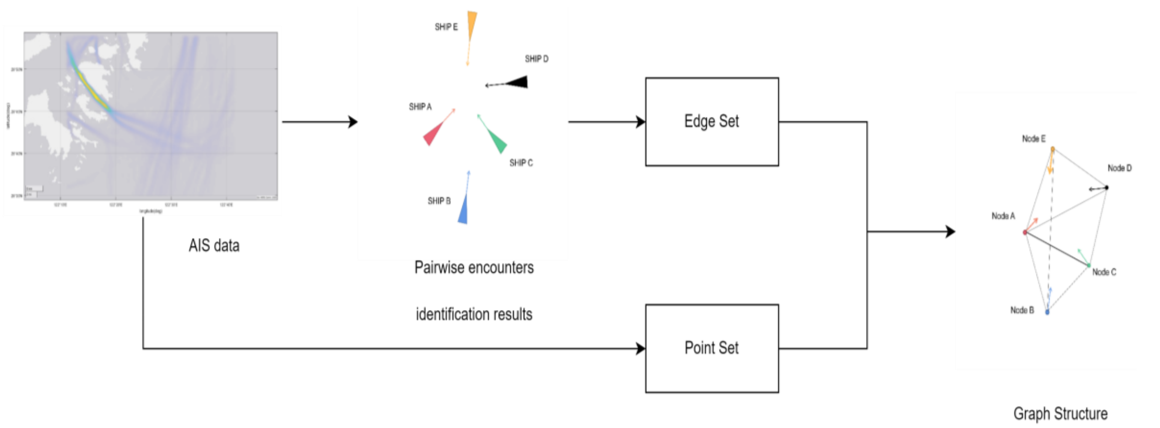


Figure 9. The identification flow of multiple ship encounters.

The vessel encounter cases were given. Figures 10 and 11 show the process of constructing discrete multi-ship encounter networks.

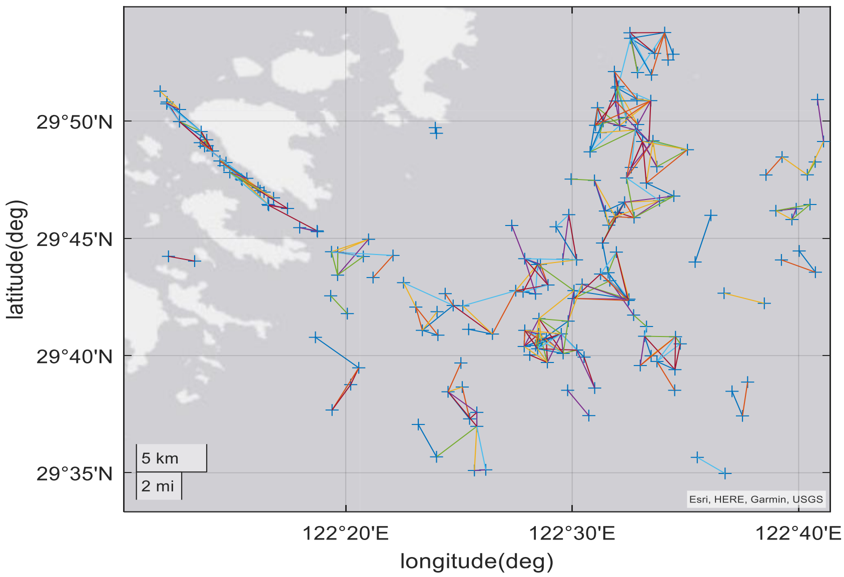


Figure 10. Ships encounter relationships based on the coordinates of vessels.

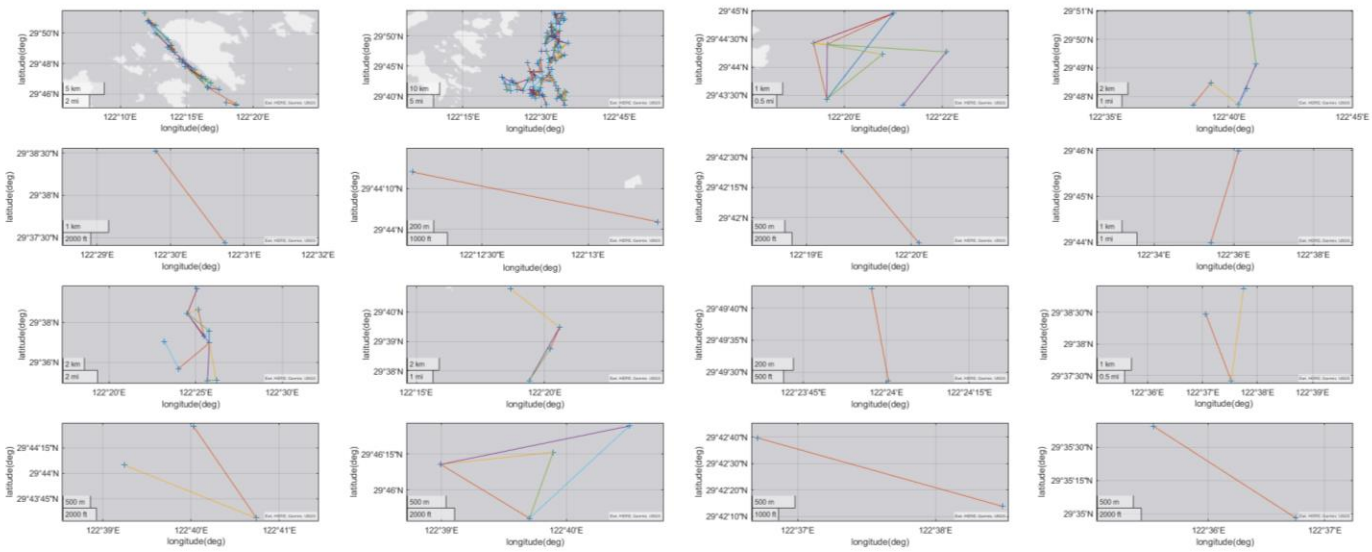


Figure 11. Ship encounter situation identification results.

4.2. Multiple Ships Encounter Situation Analysis and Continuous Spatial-Temporal Process Mining

Ship encounter graph network refers to the description of the rebirth, extinction and evolution of ship nodes and encounter relationship over time, and also refers to the process and mechanism of the formation, renewal, and alteration of network structure. The evolution of the network consists mainly of the incoming and outgoing of nodes, the increase, decrease and shift of connections, and the change of edge weights. The network evolution mechanism is an essential means to explore the network formation mechanism with specific statistical properties. It mainly involves five types of events in network evolution: ship entering the network, ship encounter relationship formation, ship encounter relationship reconstruction, ship encounter relationship cancellation, and ship exiting the network. The property of network evolution refers to the statistical law in the actual process of network evolution. In this paper, the average network degree, the average network distance, and the average network clustering coefficient are chosen to describe the interplay between the temporal and spatio-temporal evolution properties of networks and their dynamic processes.

The average distance between ships in the network is measured based on the network average distance, which indicates the size of the network and the degree of separation between nodes in the ship network. The density of ship encounters is represented by the average clustering coefficient of the network and the edge features in the multi-ship encounter network. The network average clustering coefficient is used to describe the clustering of nodes in the network, which is how close the network is. The node degree indicates the importance of the node. Based on the average degree of the network, the average number of ship nodes in the encounter case is measured. If all the ships encounter each other, it will be at most $n(n-1)/2$ for the pairwise encounter relationship. If the average clustering coefficient of the network is 0, there is no encounter relation between ships, and the encounter closeness between ships is the lowest. If the average clustering coefficient of the network is 1, the ship nodes in the network will be fully connected, and the closeness between ships will be the highest. The formula is as follows:

$$\bar{l} = \frac{2\sum_{i\ j,i\neq j}^{N} d_{ij}}{N(N-1)} \tag{5}$$

$$c_i = \frac{2m}{n(n-1)} \tag{6}$$

$$c = \frac{\sum_1^N c_i}{N} \tag{7}$$

$$\bar{k} = \frac{\sum_1^N k_i}{N} \tag{8}$$

where $\bar{l}$ represents the network distance, and d_{ij} represents the shortest distance between ship I and ship J. The number of target ships is m, the clustering coefficient of the ship is c_i, and the network average clustering coefficient is c. The node degree is k, and the network average degree is $\bar{k}$.

Giving a case of multiple ship encounters. Figure 12 shows the analyzed AIS data used for the multi-ship encounter process.

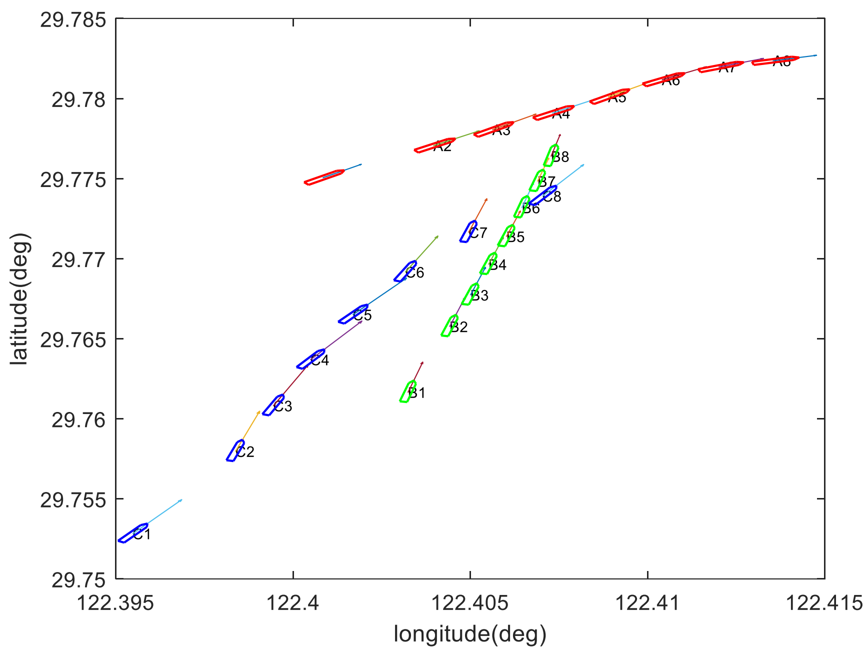


Figure 12. Schematic diagram of multi-ship encounter process.

Network average degree, network average distance and network average clustering coefficient were calculated. Figure 13 shows the multi-ship encounter process analysis results.

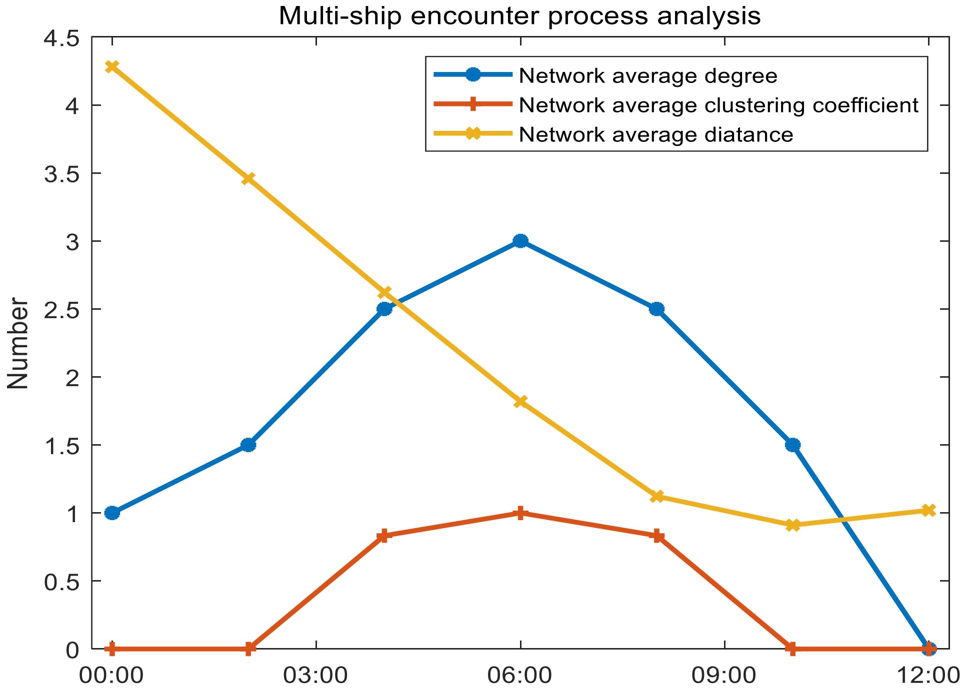


Figure 13. Multi-ship encounter process analysis.

The essence of a ship encounter is that the distance decreases first and then increases, and the situation of a ship encounter changes from simple to complex and then to simple. It can be seen from the line diagram that in the process of ship encounter, the network average distance decreases first and then increases, and the average network degree and the network average clustering coefficient increase first and then decrease. The above indexes can be used to analyze the situation and process of ship encounters. The results show that the complex network can provide an intrinsic and accessible metric to reflect the essence of marine traffic flow, which plays a vital role in understanding the marine traffic system, and managing and controlling marine traffic safety in the future.

The process of multi-ship encounters from simple to complex to simple is mined based on the process of average network degree from 0 to 0 to obtain a continuous spatial-temporal process. According to time data and identification results, the multi-ship encounter process has been recorded so that the spatial-temporal encounter process can be analyzed. Figure 14 shows the continuous historical encounter process statistics results.

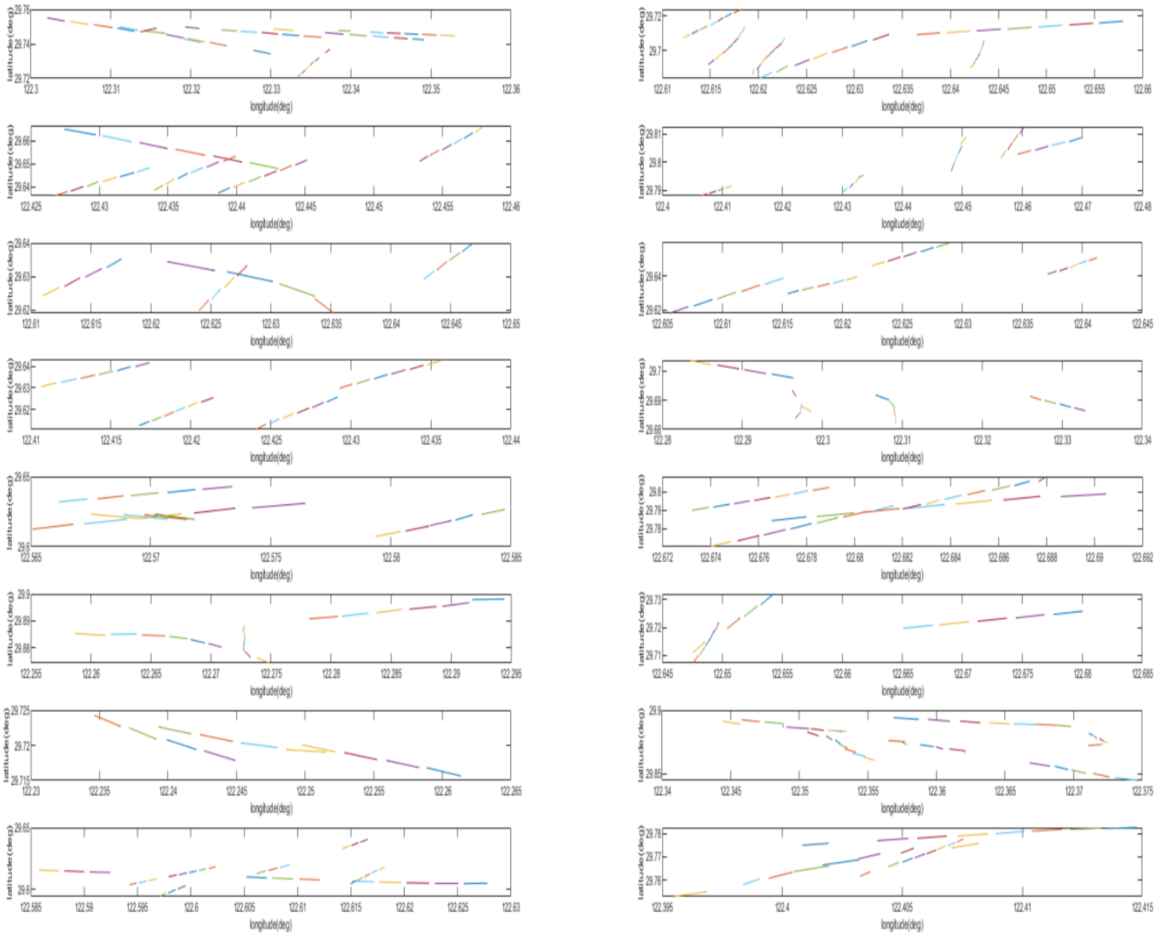


Figure 14. Historical encounter process statistics results.

4.3. Multiple Ships Coordinated Collision Avoidance Based on Risk Rank and Artificial Potential Field

For studies on multi-ship collision avoidance decision-making, most studies only consider the own ship for avoidance operation, assuming that the target ships maintain course and speed or predict the collision avoidance scheme based on the maneuvering actions of target ships [29]. “Key ship collision avoidance” is an essential rule of multi-ship collision avoidance and also an extension of the rule of two-ship collision avoidance. Mao et al. [30] identified the highest urgency vessel based on TCPA. Xiong et al. [31] proposed a multi-ship collision avoidance control method based on the speed obstacle method. Wang [32] gave collision avoidance decisions based on particle swarm optimization algorithm for global optimization considering collision risk indicator and steering angle.

In this paper, we focus on coordinated collision avoidance for multi-vessel encounter situations, which is more in line with maritime navigation practices. Multi-ship collision avoidance following COLREGS is the focus of research on multi-ship collision avoidance algorithms. Since the COLREGS cannot be directly applied to multi-ship collision avoidance, the principles of the COLREGS are mostly integrated into the avoidance effect evaluation function [31] and the “key ship collision avoidance” [33]. Zhang [34] et al. established the avoidance action model of the giving-way vessel and standing-on vessel according to the COLREGS and applied it to multi-ship avoidance. However, this approach is mainly based on pairwise encounter situations and does not consider the effect of the ship avoidance action on nearby ships. Yang [35] realized the determination of key ships for avoidance based on hierarchical modeling. Hu et al. [36] obtained the decision-making scheme by establishing the negotiation model between the give-way vessel and the stand-on vessel and defining the negotiation agreement. Ni [25] realized the optimally coordinated collision avoidance of multi-ship encounter situations based on the path planning method of queuing theory, synergetics theory, and multi-layer coding technology. HE et al. [37] not only obtained the desired formation but also solved the problem of multi-ship negotiation and coordinated collision avoidance by using the information interaction between the leader and the companion of the unmanned ship formation.

Ship collision risk was calculated based on the quaternary dynamic ship domain and fuzzy logic. Based on the geometric principle of collision avoidance, a ship collision risk calculation model is constructed. DCPA, TCPA, D, q and K are taken as the main influencing factors of the model. The collision risk indicator was calculated as [38]:

$$CRI = W \cdot U = (W_{DCPA}, W_{TCPA}, W_D, W_q, W_K) \begin{bmatrix} U_{DCPA} \\ U_{TCPA} \\ U_D \\ U_q \\ U_K \end{bmatrix} \tag{9}$$

where CRI (Collision risk index) stands for collision risk indicator, W stands for fuzzy logic, W_{DCPA} stands for coefficient of U_{DCPA}, W_{TCPA} stands for coefficient of U_{TCPA}, W_D stands for coefficient of U_D, W_q stands for coefficient of U_q, W_K stands for coefficient of U_K, U stands for membership, U_{DCPA} stands for membership of DCPA, U_{TCPA} stands for membership of TCPA, U_D stands for membership of distance, U_q stands for membership of relative bearing, U_K stands for membership of K, D stands for distance, Q stands for the relative bearing, and K stands for ship speed ratio. Based on ship movement data (such as AIS data), CRI can be obtained. The color indicates the level of danger, and the darker the color, the more dangerous it is. Figure 15 shows the schematic diagram of the collision risk model.

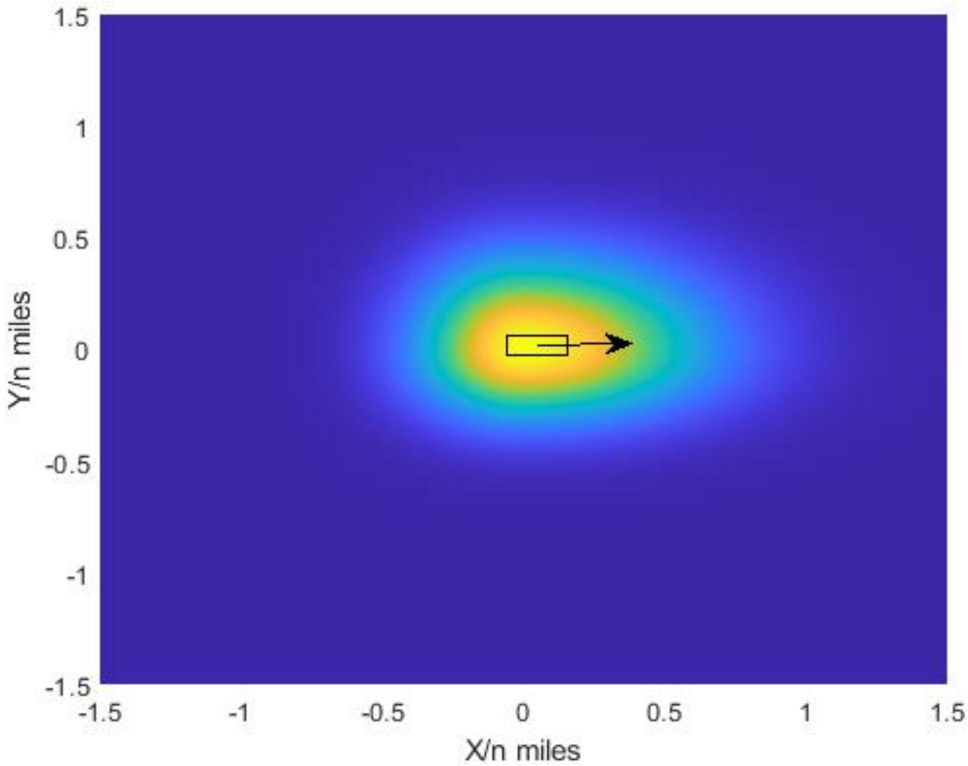


Figure 15. Schematic diagram of the collision risk model.

The ship collision risk indicator is a relative concept that depends on the length of the ship, course, speed and various other factors. For two ships in the same encounter situation, the relative distance is the same, but q is different, and the two ships perceive the conflict differently. The domain model employed in this paper is not regular, which will greatly increase the discrepancy. Although the two ships are in the same situation, the red ship thinks the situation is dangerous, but the blue ship thinks the situation is safe. The situation is in a one-way conflict. Figure 16 shows the one-way conflict diagram because of the quaternary dynamic ship domain. Each ship in a multi-ship encounter has a different perception of the collision risk indicator, so it is not possible to directly apply the fuzzy logic ship collision risk indicator evaluation method to the multi-ship encounter situation.

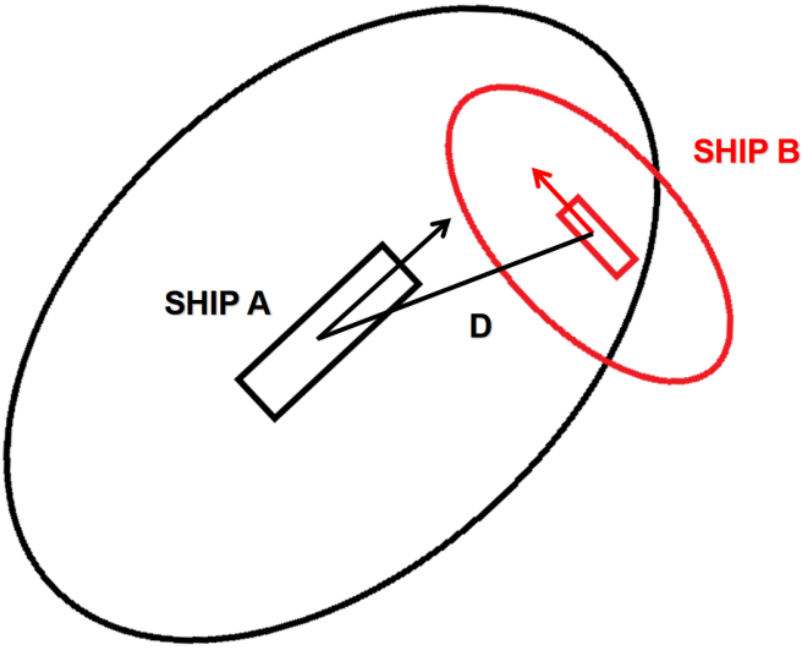


Figure 16. One-way conflict diagram.

The rank of ship collision risk to the whole situation can be calculated by the weighted PageRank algorithm. PageRank is an algorithm used by Google Search to rank websites in their search engine results. PageRank was named after Larry Page, one of the founders of Google. PageRank is a way of measuring the importance of website pages. The PageRank algorithm outputs a probability distribution used to represent the likelihood that a person randomly clicking on links will arrive at any particular page. PageRank can be calculated for collections of documents of any size. The PageRank computations require several passes, called "iterations," through the collection to adjust approximate PageRank values to more closely reflect the true theoretical value. The basic idea of the PageRank algorithm is to define a random walk model on a digraph, namely a first-order Markov chain, which describes the behavior of random walkers who visit each node randomly along the digraph. Under certain conditions, the probability of visiting each node in the limiting case converges to the stationary distribution, and then the stationary probability value of each node is its PageRank value, which represents the importance of the node. PageRank is defined recursively, and the calculation of PageRank can be carried out by an iterative algorithm.

An essential assumption of this algorithm is that the higher the input degree of a node is, the more valuable the node is. The higher the input degree of a node, the more dangerous the ship is. The pageRank calculation formula is:

$$P(X) = \alpha \sum_{Y_{i i} \in S(X)} \frac{CRI(Y_i) \times P(Y_i)}{n_i} + \frac{(1-\alpha)}{N} \tag{10}$$

where S(X) represents the set of all target ships that form an encounter relationship with ship X, ni represents the output degree of ship Yi node, N represents the total number of all ships, P(Yi) represents the PageRank value of ship Yi node, CRI(Yi) represents the calculation result of collision risk indicator with Yi as the own ship and X as the target ship, α is usually 0.85.

Based on the PageRank score and the hierarchical structure between the ship nodes, the mariners and the collision avoidance algorithms can realize coordinated collision avoidance. For the multi-ship encounter relationship case in Figure 17, the rank of the ship collision risk was given. Table 5 gave the Multiple ships collision risk rank result.

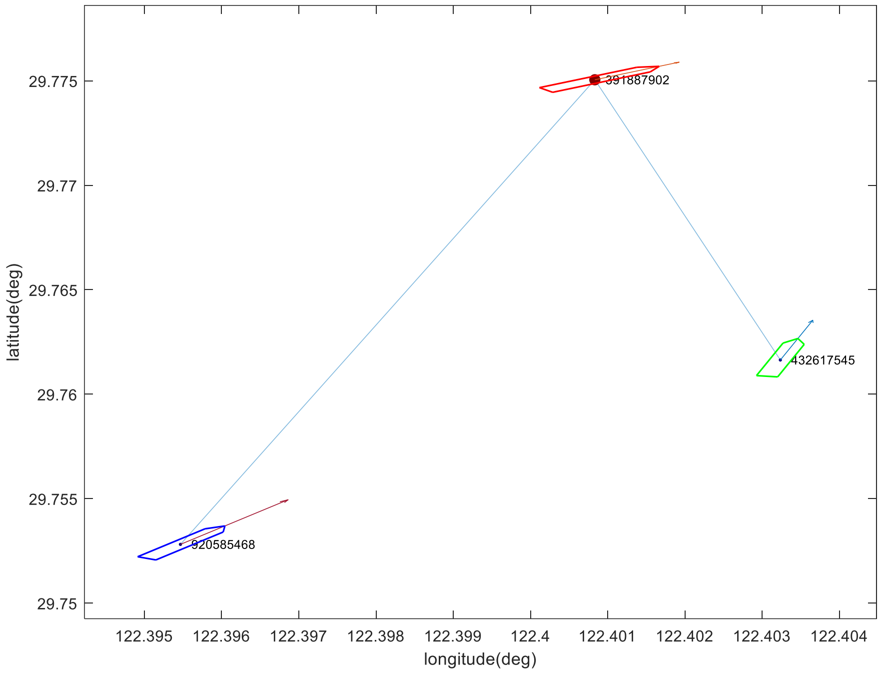


Figure 17. Multi-ship encounter relationship graph based on the coordinates of vessels.

Table 5. Multiple ships collision risk rank.

MMSI	LAT	LON	PageRank Score	Rank
391887902	29.7759	122.4008	0.3332	2
432617545	29.7616	122.4032	0.3347	1
920585468	29.7528	122.3955	0.3322	3

A ship encounter network is a system consisting of a large number of autonomous individuals. Commonly, in the absence of centralized control, ship encounter networks exhibit certain macroscopic motor behavior through local sensing and corresponding reactive behavior among individuals. Ship encounter networks are complex systems characterized by self-organized emergence, non-central control, and local interactions.

Uncoordinated ship collision avoidance actions caused numerous accidents. According to the risk rank, coordinated ship collision avoidance actions can be achieved. The higher the rank is, the earlier the ship makes collision avoidance decisions first. Then the later decision should also depend on the earlier decision results. Figure 18 shows the multi-ship encounter decision-making process.

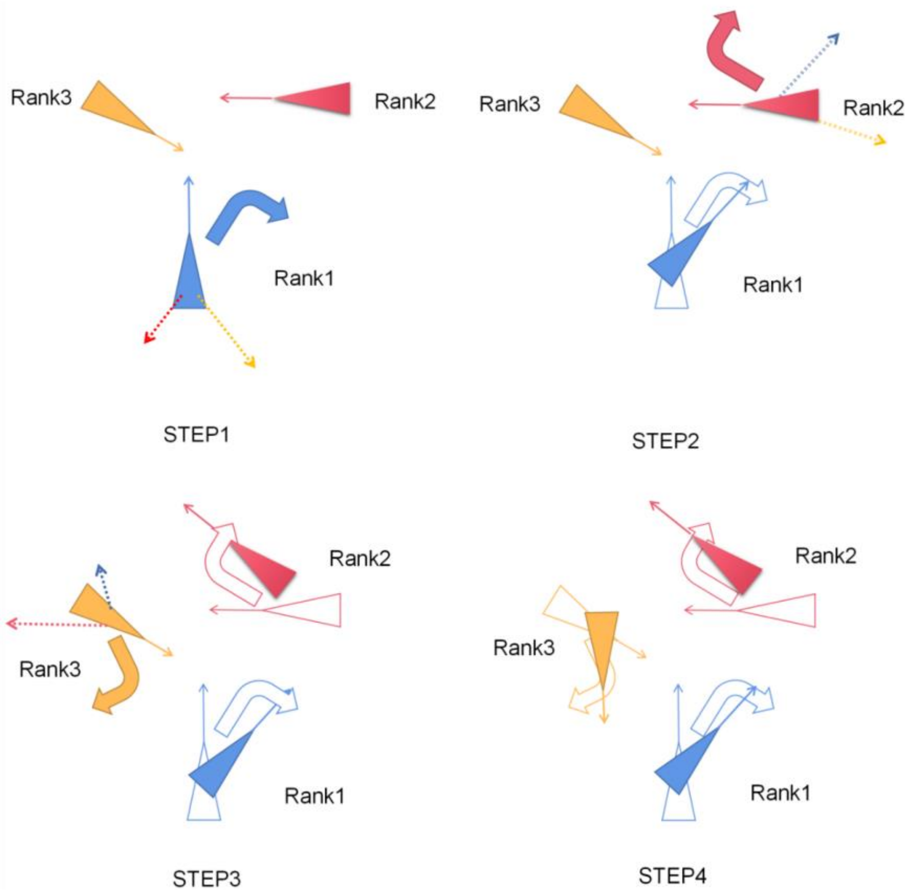


Figure 18. Multi-ship encounter decision-making process.

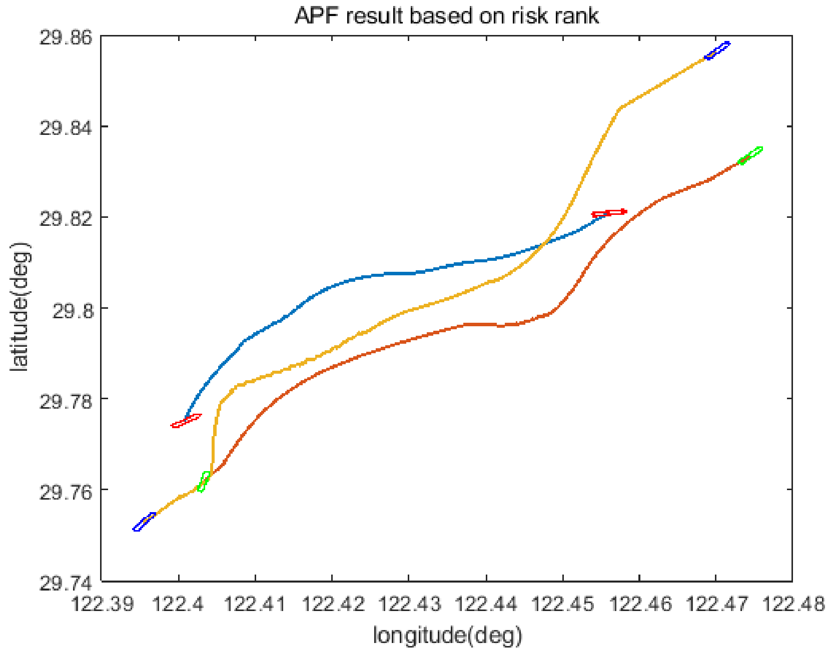
Assume that the coordinates of the ship at this time are $q = (x, y)^T$, then the resultant force field constructed by APF (Artificial Potential Field) can be expressed as:

$$U(q) = U_{att}(q) + U_{rep}(q) \tag{11}$$

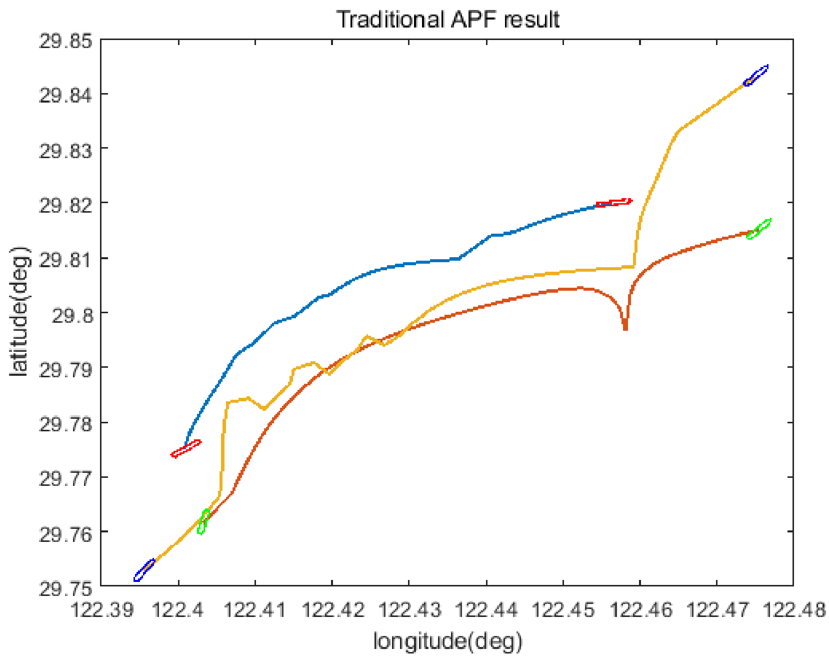
where $U(q)$ represents the resultant force field, $U_{att}(q)$ represents the gravitational field generated by the target, and $U_{rep}(q)$ represents the repulsive force field composed of each obstacle. According to the definition of APF, the negative gradient of the potential field at the point where the ship is located is the resultant force on the ship at that moment. Therefore, the resultant force formula of this point can be obtained according to Equation (12):

$$\overrightarrow{F(q)} = -grad(U_{att}(q)) - grad(U_{rep}(q)) \tag{12}$$

With risk rank based on the CRI and the weighted PageRank algorithm, ships can take fewer coordinated actions to avoid a collision, while the traditional APF method takes more actions to avoid a collision. Figure 19 contrasts the artificial potential field result based on risk rank with the traditional artificial potential field result. The results also prove the correctness of the risk rank.



(**a**)



(**b**)

Figure 19. Artificial potential field result based on risk rank (**a**); traditional artificial potential field result (**b**).

5. Conclusions

Ship collisions cause heavy losses, and multiple ships encounter situations that are especially dangerous. In multiple ship encounter situations, OOW and the maritime management departments think it's seriously difficult to identify, analyze the situation and make collision avoidance decisions. Single ship data was combined into a ship encounter network based on pairwise encounters identification results. In order to accelerate the rate of pairwise encounter identification, a "spatial-temporal companion" was used. The principles of pairwise encounter identification in COLREGS were listed. Three cases of pairwise encounter identification were given to prove the correctness of the method.

Complex network theory has been used to describe the interplay between the temporal spatial-temporal evolution properties of a network and its dynamical processes. In this paper, the average network degree, the average network distance, and the average network clustering coefficient are chosen to describe the interplay between the spatial-temporal evolution properties of networks and their dynamical processes. Based on the recognition results of pairwise encounter identification results, a discrete multi-ship encounter network is constructed. The process of multi-ship encounters from simple to complex to simple is mined based on the process of average network degree from 0 to 0 to obtain a continuous spatial-temporal process. The results can be used for multi-ship encounter situation awareness, multi-ship collision avoidance decision-making and channel navigation evaluation, and also provide data for machine learning.

Quaternary dynamic ship domain and fuzzy logic were used to calculate CRI, but it can only be suitable for certain ships and cannot be suitable for the whole network. The weighted PageRank algorithm was used to give risk rank to the whole network, which is essential to "key ship collision avoidance." With the risk rank based on CRI and weighted PageRank algorithm, ships can take fewer coordinated actions to avoid collisions. The result also proves the correctness of the risk rank measure result. In the future, the risk rank measure method combined with other collision avoidance will be further studied, and more testing will be required. The isomorphism of the graph will be further studied so that it can be used to select the same multiple ship encounter situations from the AIS data to assist collision avoidance.

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