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Research on the methods of ship's autonomous collision avoidance in complex environment

Hongguang Lyu

WORLD MARITIME UNIVERSITY

Dalian, China

RESEARCH ON THE METHODS OF SHIP'S AUTONOMOUS COLLISION AVOIDANCE IN COMPLEX ENVIRONMENT

By

Lyu Hongguang

The People's Republic of China

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature): ………………………

(Date): August 27, 2021

Supervised by: ………………………

Supervisor’s affiliation: Professor of Navigation College，DMU

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ABSTRACT

Title of Research paper: **Research on the methods of ship's autonomous collision avoidance in complex environment**

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Under the background of Maritime Autonomous Surface Ships（MASS）, this paper studies how to carry out automatic collision avoidance and path planning in complex navigation waters, and verifies it by simulator.

This paper briefly reviews the current international and domestic research status in the field of ship automatic collision avoidance. Considering the difficulties and problems encountered in the current research, the data modeling method, collision risk judgment, automatic collision avoidance decision-making suggestions and simulation verification of collision avoidance methods in complex navigation environment are studied.

This paper studies the accurate modeling of various polygons in complex navigation environment, including concave polygon obstacles, which provides decision-making basis for automatic collision avoidance algorithm. According to the requirements of manned ship and remote control ship, a fast pre calculation scheme of collision avoidance decision is proposed. Through the construction and experimental verification of the simulator environment, the ship automatic collision avoidance decision-making method in complex navigation environment has obtained convincing test results.

This research will help to promote the further development of MASS, reduce the workload of crew and ensure the safe navigation of ships.

KEY WORDS: Autonomous Collision Avoidance; Path planning; Complex Environment；Electronic Chart; Environment modeling; MASS

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LIST OF ABBREVIATIONS

ACO	Ant Colony Optimization
AIS	Automatic Identification System
ANN	Artificial Neural Network
APF	Artificial Potential Field
BEA	Bacterial Evolutionary Algorithm
CA	Collision Avoidance
CC	Checking Criterion of Collision Risk
CD	Checking Distance of Collision Risk
COLREGs	International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
CPP	Cooperative Path Planning
DCPA	Distance at Closest Point of Approach
DVS	Dynamical Virtual Ship
EA	Evolutionary Algorithm
EC	Evolutionary Computation
ECDIS	Electronic Chart Display and Information System
EMCA	European Maritime Safety Agency
ENC	Electronic Navigational Chart
FL	Fuzzy Logic
FMM	Fast Marching Method
IMO	International Maritime Organization
LOA	Length overall
LOS	Line of Sight
LOSCAN	Line of Sight Counteraction Navigation
MASS	Maritime Autonomous Surface Ships
MPC	Model Predictive Control
OS	Own Ship
PAD	Predicted Areas of Danger
PD	Proportion Differentiation
PGHAPF	Path-Guided Hybrid Artificial Potential Field
PID	Proportion Integration Differentiation

PIDVCA	Personifying Intelligent Decision-making for Vessel Collision Avoidance
PSO	Particle Swarm Optimization
RRT	Rapidly-exploring Random Tree
TBA	Trajectory Base Algorithm
TCPA	Time to Closest Point of Approach
TS	Target Ship
TSS	Traffic Separation Schemes
UAV	Unmanned Aerial Vehicle
VLCC	Very Large Crude Carrier
VO	Velocity Obstacles
VTS	Vessel Traffic Service
WPT	Waypoint

1 INTRODUCTION

1.1 Research background

Today, navigation technology is highly developed, However, ship collision, grounding accidents still occur frequently. According to the 2019 report of the European Maritime Safety Agency (EMCA), between 2011~2017, 53.1% of accidents at sea are navigation accidents such as grounding, collision, etc.(Emsa, 2018). IMO research shows that, more than 80% of global accidents are caused directly or indirectly by human factors. To ensure the safety of ships, the autonomous ship is a necessary and effective way to solve the problem of human factors. It can also fundamentally eliminate or reduce human factors caused by collision accidents, to make navigation safer and reach the goal of cleaner oceans.

1.1.1 International developments and trends

Since 2017, continued MSC sessions of IMO have been focused on the issues related to MASS (Maritime Autonomous Surface Ships). And they have initiated a study on the adaptation of existing convention standards with MASS, decided to develop MASS testing guidelines and the provisional guidelines for MASS testing (Imo, 2017, 2019a, 2019b). Rolls Royce completed the collision avoidance project (MAXCMAS) for MASS in 2017. They claim that its autonomous navigation meets the requirements of the 1972 International Rules for Collision Avoidance at Sea (COLREGs) (Varas et al.). In addition, the completed delivery of the world's first autonomous container ship Yara Birkeland, the sea test of the world's first remote control autonomous ferry SVAN, the world's first sea trial of MASS autonomous navigation systems in the Iris Leader (a Ro-Ro ship owned by Japan's NYK), and AI

Captain of the Mayflower Autonomous Ship at present days, all of which are important historical events in the field of autonomous navigation of autonomous ships. These latest advances intensifies the urgency of research on ship autonomous navigation technology for China.

1.1.2 Research background at home

General Secretary Xi Jinping put forward the strategic goal of building a maritime power and a transportation power in the report of the Nineteenth National Congress of the Party. Under the background that the world is about to enter the development period of "industry 4.0" with intelligent manufacturing as the core, the plan "Made in China 2025" focuses on high-tech ships and intelligent ship manufacturing. Maybe the development of autonomous ships will effectively solve the main problems faced by ships in energy saving and emission reduction, manpower cost and ship safety (严新平, 2016). May 2019, 7 departments such as the Ministry of Transport jointly issued the "Intelligent Shipping Development Guidance", to build the Global Intelligent Shipping Development and Innovation Center in 2025.

From the international and home research focus and national strategy, the selection of the topic "methods of ship's autonomous collision avoidance in complex environment" is of great significance at present.

1.2 Research status and the existing problems

1.2.1 Research status and development trend at home and abroad

In recent years, more research about MASS abroad has improved rapidly. However, most of them are still in theoretical research and laboratory simulations, not up to the level of installation or application in ocean ships. The COLREGs compliance, completeness, robustness and real-time performance of these research still need to be improved.

Research institutions include the Massachusetts Institute of Technology, the Polish Maritime Institute, the Norwegian University of Science and Technology, the Netherlands University of Delft Technology, the University of London College, and so on.

At present, the algorithms used in literature research include: model predictive control method (B. O. H. Eriksen, Breivik, Wilthil, Flaten, & Brekke, 2019) (Johansen, Perez, & Cristofaro, 2016), CPA and IVP based methods (Woerner, 2016), collaborative path planning algorithm (CPP) (Tam & Bucknall, 2013), artificial potential field method (APF) (S. M. Lee, Kwon, & Joh, 2004) (Xue, Clelland, Lee, & Han, 2011) (Hongguang Lyu & Yin, 2019), velocity obstacle (VO) (Kuwata, Wolf, Zarzhitsky, & Huntsberger, 2014), fast matching method (FMM) (Y. Liu, Song, Bucknall, & Zhang, 2019; Song, Liu, & Bucknall, 2017), A* algorithm (Song, Liu, & Bucknall, 2019), trajectory base algorithm (TBA) (Lazarowska, 2017), The ant colony algorithm (ACO) (Lazarowska, 2015), Various evolutionary algorithms (EA) (Szlapczynski, 2015), Fuzzy logic (FL), artificial neural network (ANN), Deep learning (Lokukaluge P. Perera, 2020; Zhao & Roh, 2019) and some comprehensive intelligent algorithms (Ahn, Rhee, & You, 2012; Brcko & Svetak, 2013; L. P. Perera, Carvalho, & Soares, 2012). Fewer autonomous avoiding collision algorithms can consider COLREGs, handle static obstacles and dynamic ships simultaneously. Some algorithms have long computational time, not real-time, and some algorithms assume that target ship can act according to COLREGs, or keep course at a constant speed.

The main institutions at home engaged in this research include: Harbin Engineering University, Dalian Maritime University, Wuhan University of Technology, Jimei University, Shanghai Maritime University, Jilin University, and their research method is similar to that of foreign literature. It should be noted that professor Li of Jimei

University put forward the theory of the personifying intelligent decision-making for vessel collision avoidance (PIDVCA) (李丽娜, 陈国权, 李国定, 郑敏杰, & 孙洪波, 2014; 李丽娜 et al., 2009), using an integrated AI decision-making method to construct the system by combining mathematical analysis, machine learning, expert system principles, fuzzy mathematics and navigation knowledge. This practical application of automatic collision avoidance system is a big step for MASS. In addition, Dr. Sun(孙立成, 2000), Dr. Bi (毕修颖, 2000) and Dr. Zheng(郑中义, 2000) of Dalian Maritime University had great influence on collision risk and automatic collision avoidance algorithm. Moreover, other related studies include Dr. Yang's multi-agent approach (杨神化, 2008), Dr. He's numerical work of COLREGs (He et al., 2017), Dr. Xiong's VO method(熊勇, 贺益雄, & 黄立文, 2015), Dr. Zhang's dynamical virtual ship (DVS) (Zhang, Deng, & Zhang, 2017), Dr. Shen's deep competition Q-learning algorithm and A* algorithm(沈海青, 郭晨, 李铁山, & 余亚磊, 2018), Dr. Xue's method of collision avoidance with key ships(薛彦卓, 2014) and artificial potential field method (Hongguang Lyu & Yin, 2019; Xue et al., 2011).

Based on the comparative analysis of domestic and foreign literature, autonomous navigation and collision avoidance is the focus of research in the field of autonomous ships. However, the research difficulties are mainly reflected in the complexity of marine navigation environment and the multi-constraint attributes of collision avoidance decision, such as the coexistence of complex static obstacles and multi ships, the inevitable disturbance of wind, wave, flow and other external environment, the COLREGs compliance is still required, the kinematics and dynamics characteristics need to be considered, and the real-time robust and deterministic decisions should be guaranteed. At least two important scientific hypotheses are needed to complete the above key technologies: **high precision modeling of complex navigation environment and robust collision avoidance decision**

algorithm with multiple constraints.

1.2.2 Precise modeling of complex navigation environment

Modeling of environment is the basis of designing autonomous collision avoidance algorithm. In recent years, with the continuous development of MASS concept and related technology, modeling scenarios have gradually turned to complexity, precision and practicality.

The number, state and data source of the ship (Own Ship, OS) encounter dynamic ship collision avoidance: from the direction of dealing with collision avoidance between two ships to the direction of collision avoidance with multi ships (Huang, Chen, & van Gelder, 2019; Karbowska-Chilinska et al., 2019; Lazarowska, 2017; Hongguang Lyu & Yin, 2019; Woo & Kim, 2020); from the assumption that the uniform linear motion state of the target ship to the situation that the target ships move randomly or even take incongruous collision avoidance action (Hu et al., 2020; Huang, Chen, Chen, Negenborn, & van Gelder, 2020; Hongguang Lyu & Yin, 2019), or can coordinate with the OS to take collision avoidance action (B. O. H. Eriksen et al., 2019; Zhao & Roh, 2019; 沈海青, 2018); from the direction of researchers assuming the movement data of target ship to the real historical data (Chen, Huang, Papadimitriou, Mou, & Gelder, 2020; Lazarowska, 2019) and real-time data (Kufoalor, Johansen, Brekke, Heps, & Trnka, 2019) using the automatic identification system (AIS) in busy waters. Although these studies can provide real-time samples of target ship data with uncertain motion characteristics, it is difficult to complete the dynamic interaction with the test data, and cannot simulate the navigation environment of manned ship and unmanned ship.

In addition to modeling multi ship encounter situations, some new collision avoidance algorithms can also deal with static obstacles. However, in the modeling process, the static obstacle is reduced to point and its expanded circle (Abdelaal, Franzle, & Hahn, 2018; Hongguang Lyu & Yin, 2019) or elliptical (B. r.-O. H. Eriksen, Bitar, Breivik, & Lekkas, 2020), or the minimum external circle (Ma, Hu, & Yan, 2018) of irregular figure, and even processed into a simple combination of points (Sun, Wang, Fan, Mu, & Qiu, 2018; Zaccone & Martelli, 2020). Although the Hu et al. algorithm (Hu et al., 2020) is applied to the restricted water area, the collision avoidance test area of the ship is artificially delimited within a polygon of navigable water area, in which the static obstacle is also a point mark. Niu et al. can deal with complex terrain (Niu, Savvaris, Tsourdos, & Ji, 2019), shoreline, but cannot deal with underwater obstacles (such as shoals, reefs, etc.), cannot avoid collision with dynamic other ship and consider COLREGs, which is belong to a static path planning. At the same time, these methods have the advantages of simple modeling, but they cannot accurately describe and integrate the complex environment of autonomous ships, so it is difficult to apply in practice.

From the application level, the modeling of complex navigation environment, at present, is represented by grid map (Hinostroza, Xu, & Soares, 2019; X. Liu, Li, Zhang, & Yang, 2019; Song et al., 2019; Wen, Zhang, Liu, & Wu, 2019). However, it is limited by resolution, the accuracy of environment map, and that different types of obstacles cannot be classified and processed, for example, islands and reefs, shore lines, shallow water areas, sunken ships, navigation aids, waterway boundaries and so on. They are complex in shape, different characteristics, and different requirements for collision avoidance. By simplifying the contour of obstacles to construct polygonal or rasterized environmental maps, the information of navigable waters or obstacles will be distorted, and their respective characteristic attribute cannot be guaranteed (X. Liu et al., 2019; Szlapczynski & Szlapczynska, 2017). Especially when the reliability and intelligence of path planning are greatly reduced through complex waters where different types of obstacles coexist.

Some progress has been made in data modeling by electronic navigational chart (ENC) for navigation environment of autonomous ships (Tsou, 2016), which is a direction of autonomous ship navigation environment modeling (M.-C. Lee, Nieh, Kuo, & Huang, 2019; Song et al., 2017). ENC-based electronic chart display and information system (ECDIS) is an internationally recognized good carrier for the overall environmental information representation of ships. ECDIS can provide accurate static data such as water depth, obstacles, land area, Ships can also integrate dynamic data from various sensors such as GPS, radar and AIS, and easily be combined with the autonomous collision avoidance decision system of merchant ships. Therefore, the ideal model of autonomous ship navigation environment should be adapted to the ENC data structure. Tsou's modeling of vector chart data based on ECDIS framework (Tsou, 2016), whose essence is to create a simplified point, line, surface obstacle buffer, is combined with a hexagon Predicted Areas of Danger (PAD) to find the path of collision avoidance without intersection with buffer and PAD. This method can take considering some COLREGs for collision avoidance, but assume that all target ships always keep their direction, and without considering the characteristics of the ship's motion and the properties, also environmental modeling is not based on the coupling of ENC and dynamic uncertainty. Therefore, difficulty in this respect is how to express complex ENC data into an accurate environment model that can be recognized and interacted by automatic collision avoidance algorithm. At the same time, the coupling modeling of other ship information with dynamic uncertainty is taken into account.

1.2.3 Multi-constrained Automatic Collision Avoidance

The complexity of navigation environment for MASS, determines the requirements of environment modeling, and the highly complex constraints for the automatic collision avoidance algorithm in planning problems (Zhou et al., 2020). At a minimum, these constraints include: COLREGs compliance; environment aspects, such as restricted waters (considering static obstacle modeling), the number and maneuverability of other ships (variable course and speed change), external environment disturbances, etc.; constraints of ship motion, such as trajectory smoothing, manipulation characteristics constraints, variable speed avoidance except steering, etc.; algorithm performance; timeliness, robustness, repeatability or certainty. Related research at home and abroad focuses on the autonomous collision avoidance algorithm with less constraints. The more constraints, the more complex the coupling and checks and balances within the algorithm, the more difficult when it is to be implemented. On the basis of previous research, the representative literature in this field has been selected in recent years, and **3 core algorithms** have been summarized from the perspective of methodology, and their performance in four aspects of rules, environment, ontology and performance has been analyzed in detail to find out the remaining problems and the direction of efforts in this field.

① Model Predictive Control (MPC) method has the advantage of natural multi-model constraint processing, which can be combined well with perception, planning and control. Therefore, good application has been made in the field of autonomous collision avoidance of ships. Eriksen et al. proposed a method of branch heading MPC (BC-MPC) to overcome the noise in obstacle detection, improve robustness of collision avoidance algorithm (B. O. H. Eriksen et al., 2019). This method can consider Article 8 and Article 17 of the COLREGs, a preference for compliance with articles 13~15, and the actual ship test of the unmanned craft, but outcome trajectory wasn't smooth enough, and unable to handle static barriers. To that end, The team designed a three-tier integrated collision avoidance system (COLAV) (B. r.-O. H. Eriksen et al., 2020)，including (1) advanced path optimization layer, (2) intermediate MPC- based dynamic obstacle conventional collision avoidance layer and (3) low-level BC-MPC-based emergency collision avoidance layer to improve trajectory smoothing, but the algorithm itself is still unable to deal with complex static obstacles, Similar shortcomings are found in the finite control set MC-MPC method (Sun et al., 2018). Similar studies have been conducted by Kufoalor et al.(Hagen, Kufoalor, Brekke, & Johansen; Kufoalor et al., 2019). In particular, emergency collision avoidance, test verification of collision avoidance algorithm are conducted, but this method can't avoid static obstacles. In sum, the weakness of the MPC method lies in the collision avoidance of mixed ships and complex static obstacles, especially in the ENC data environment of various static obstacles.

② Artificial Potential Field (APF) based method has the property of deterministic solution, easy modeling, fast computation, handling static obstacles and dynamic ships, COLREGs compliance, but there is also a local minimum problem in the process of solving. A priori path-guided hybrid artificial potential field method (PGHAPF) (Hongguang Lyu & Yin, 2019) proposed by our school, can make environmental modelling of restricted waters based on electronic nautical charts, and a real-time and COLREGs constrained collision avoidance algorithm which can deal with multiple ships considering ship kinematics. However, a great deal of research is needed on automatic modeling of environment based on ENC data, mechanism of collision avoidance algorithm and its testing. Poland Lazarowska use discrete artificial potential field method (DAPF) to achieve multi-ship collision avoidance (Lazarowska, 2019, 2020). His simulation test is carried out based on the AIS historical data collected Horyzont II the training ship. Besides, the algorithm based on raster chart modeling, by setting the historical cell potential field value infinity, to overcome the problem of local minimum but not fully verified in the study. Based on course change and track retention Lee et al designed a two-mode velocity potential field method (M.-C. Lee et al., 2019), to achieve multi-ship collision avoidance algorithm with COLREGs constraints in open waters. The main problem with these studies is that complex waters are not applicable, environmental modeling is not based on ENC data, the corresponding collision avoidance strategy is only steering without variable speed, local minimum problem has not been completely solved (Huang et al., 2020).

③ The application of autonomous multi-objective optimization algorithm in the field of automatic collision avoidance. Hu et al. designed a hierarchical sorting rule, prioritizing speed change preference over other optimization objectives such as path length and smoothing (Hu et al., 2020). A hierarchical multi-objective particle swarm optimization (H-MOPSO) are included in the algorithm, which is a near real-time multi-ship collision avoidance algorithm with COLREGs constraints, including variable speed avoidance. Also, it is conducted collision avoidance tests with four other ships on the simulator test platform, based on the electronic chart environment, but no modeling of static barriers. Compared to PSO, beetle antennae search (BAS) method proposed in 2017, is relatively efficient because of just one individual, less computation, fast convergence, and the strong global search ability. Xie et al. (Xie, Xiumin, Zheng, & Liu, 2019) use a 3- DOF ship model to establish optimization problems with COLREGs as control constraints, then a real-time collision avoidance prediction optimization strategy is realized by improving the BAS algorithm. But at present, this method can only avoid two other ships, cannot cope with complex environments including static barriers. Wang et al. proposed an improved Ant Colony Optimization (IACO) method have similar problems (H. Wang, Guo, Yao, He, & Xu, 2019), although it can alter course and change speed in the collision avoidance, the motion model of unmanned craft is not considered. To sum up, the main problem of multi-objective optimization algorithm in this field is that it is difficult to deal with the complex environment containing static obstacles.

1.2.4 Existing problems

Through the above analysis, the main problems in the research of automatic collision avoidance algorithm include:

(1) The modeling environment is simple, most studies do not build static obstacle model based on electronic chart environment, there are some problems of small number of other ships, insufficient flexibility and most of them do not consider external environment disturbance, so it is difficult to apply to restricted waters;

(2) From the performance of the algorithm, most algorithms do not have the ability of emergency collision avoidance decision, and the robustness and real-time performance still need to be further strengthened to deal with the high speed dynamic complex situation. In addition, it should be paid attention to the deterministic features of the algorithm, otherwise it is difficult to obtain the application in the real ship environment.

Unmanned ship or MASS has become a hot research topic in the field of international, domestic and industry development, but from the current theoretical research and technical level, or industry and shipbuilding intelligent certification, it has not reached the level that MASS can operate independently in complex waters, which is an insurmountable problem in MASS research.

Therefore, automatic collision avoidance/risk avoidance decision in complex waters will be the focus of this study.

2 MODELING OF COMPLEX ENVIRONMENT

2.1 Basic ideas

Vector electronic chart data, which can represent the environmental information accurately. In particular, Electronic Chart Display Information Systems (ECDIS) using Electronic Navigational Chart (ENC) data have become a good carrier of global environmental representation. As providing accurate static data such as water depth, obstacles, land domain, and the dynamic data of various sensors such as GPS, radar and AIS, it is easy to be integrated for autonomous collision avoidance (CA) decision-making system. Therefore, the ideal model of unmanned ship navigation environment should fit with the data structure of electronic charts.

The vector electronic chart required by S-57 standard, even its spatial vector data expression, basically takes the form of point, line and surface. Therefore, establishing static environment model in the form of geometric vector, lines and faces of polygons should be the focus. Based on the vector chart data modeling under the ECDIS framework, MC Tsou (Tsou, 2016) adopts the Predicted Areas of Danger (PAD) and evolutionary calculation method. The proposed method obtains the shortest possible path by detecting if there are intersections between the point, line, surface object buffer, and PAD, considering COLREGs, but without considering the dynamic characteristics of the ship and the property information of different obstacles. Song et al. (宋利飞, 2015) proposed a vector island winding method based on Shapefile electronic chart to solve the problem of environmental information loss or the optimization of environmental planning, and verified the superiority of the algorithm in intelligence and time consumption through simulation. However, the algorithm is mainly for global offline planning, and still fails to classify different types of obstacles to optimize the planning path. Also the algorithm does not consider the situation of unmanned ships encountering both static obstacles and dynamic TSs, and the change of initial planning path may lead to collision with nearby static obstacles.

In addition, the complex environment constructed should include autonomous ships, which interact with the natural environment at sea, especially the sea and obstacles. Therefore, the precise modeling of autonomous ships is also very important, not using the method of reducing ships to prime points as in most studies, the precise mathematical model and control model should be established. The above together constitute the complex environment of autonomous ship navigation.

2.2 Environmental modeling based on vector chart

Chart vector data in the S-57 standard, such as point, lines, and face elements may correspond to different types of obstacles, which are shown in Table 2.1. Therefore, the corresponding path planning is handled differently. By inquiring the attribute information of the point, line and surface elements, the type of object and risk degree can be defined, and then different safety distance with them can be selected for path planning.

Table 2.1 Spatial vector data model in S-57 standard

content	S-57	obstructions（including, but not limited to）
point	node	Various isolated reefs, shipwrecks, navigation aids, shallow points, etc.
line	edge	Safety contours, land boundary, channel boundary, etc.
plane	face	Large artificial or natural regional markers or obstacles

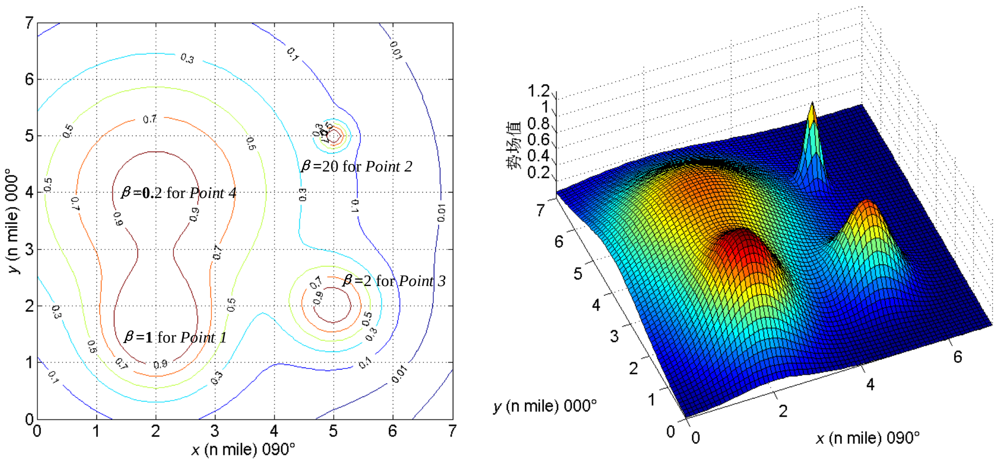
2.2.1 Point-element potential field

First, establish the potential field of the point element, in a two-dimensional plane environment with M point obstacles, the coordinate $p_i(x_i,y_i)$, and the repulsive potential field $f_{point}(p)$ at arbitrary point $p(x, y)$ can be expressed as (吕红光 & 尹勇, 2019):

$$f_{point}(p) = \sum_{i=1}^{M} f_i(p) = \sum_{i=1}^{M} e^{-\beta_i \cdot d_i^2} \tag{2.1}$$

Where $f_i(p)$ is the repulsion potential field corresponding to the i obstacle, β_i is the tunable positive coefficient of the potential field, and d_i is the distance between the p point and the p_i point, represented as $d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$. Figure 2. 1 shows the equipotential range diagram a) and potential field surface diagram b) for four point obstructions p_1(2,1.5), p_2(5, 5), p_3(5,2) and p_4(2,4) corresponding β_1=1, β_2=20, β_3=2 and β_4=0.2, where the p_2 potential field with large β value is the steepest and the smallest influence range, while the p_4 potential field with smaller β is the slowest and the largest influence range. The equipotential line (potential field) reaches the maximum value 1 at the obstacle position (center); the farther the periphery from the obstacle, the smaller the potential field value (outermost circle), and the potential closer to 0 means the smaller risk.

Combined with the practice of navigation, this paper proposes a point-like obstacle modeling method for different types and hazard degree: to determine the influence range of different types of obstacles based on β value and the hazard area around obstacles based on potential field value. Furthermore, if the obstacle (including its potential field) is within the range of other obstacle potential fields, an obvious superposition effect appears, the area between p_2 and p_3 in Figure 2. 1. The degree of danger in the potential field superposition region is determined by the total potential field value of the superposition region. If the setting potential field value is less than 0.5 is safe, then the traffic between p_1 and p_3 is still navigable; if the setting potential field value is less than 0.01 is safe, no navigation passage between p_1, p_2, p_3 and p_4 because they are combined into integrated obstacles.



a) equipotential range diagram b) potential field surface diagram

Figure 2. 1 Potential contour & surface of point obstacle for different β value

When modeling the electronic chart environment, it is necessary to determine the category of the obstacle according to the object attribute, and then determine the safe distance maintained from it. For application, represent the distance d_i from a point obstacle in n mile as a function of potential field values $f_i\ (p)$ and β_i:

$$d_i = \sqrt{\frac{\ln f_i(p)}{-\beta_i}} \tag{2.2}$$

Figure 2. 2 shows the functional relationship between the distance (transverse coordinate) of our ship and the point obstacle, and the resulting potential field value (longitudinal coordinates) under 8 typical β values. Here the smaller the β, the slower the potential field attenuation, the large influence range, (e.g. the difference of the potential of β =0.5 and β =5). The larger the β, the faster the potential field decay, exhibits steep, small influence range, and the weaker the β regulates the range (such as very close between β =50 and β =500).

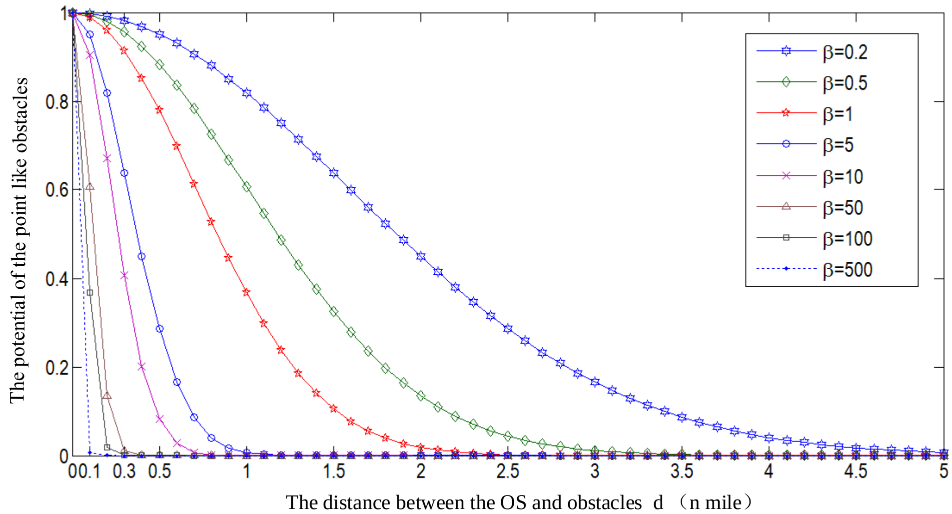


Figure 2. 2 Relationship of the potential and the distance (between the OS and point obstacle) for different *β*

Source：吕红光, & 尹勇. (2019). 基于电子海图矢量数据建模的无人船路径规划. *交通信息与安全*, *37*(05), 94-106.

If a small potential field value such as λ =0.01 is the critical safety potential field value, it is considered safe when a ship sails in an area less than the potential field value. Accordingly, establish the corresponding relationship and recommended values *β* for spatial objects with different attributes and safety distance between our ship and obstacles, as shown in Table 2.2.

Table 2.2 Suggested *β* for spatial objects with different attributes and safety distance (λ=0.01)

β	safe distance (n mile)	Example of the obstacle category	Example of coding
0.2	4.80	rock uncovered， small Island	LNDELV， LNDARE
0.5	3.03	rock awashed, reef	UWTROC
1	2.15	Dangerous wreck	WRECKS
5	0.96	Light ships, isolated dangers, obstructions, sea platforms, etc.	LITVES， BOYISD， OBSTRN， OFSPLF
10-20	0.68-0.48	cardinal marks	BOYCAR
50	0.30	lateral marks	BOYLAT
100	0.21	safe water marks	BOYSAW
500	0.10	Avoid too proximity	/

Source：吕红光, & 尹勇. (2019). 基于电子海图矢量数据建模的无人船路径规划. *交通信息与安全*, *37*(05), 94-106.

It should be noted that the setting of the safe distance between unmanned ships and obstacles is also related to the navigation waters, meteorological conditions, maneuvering performance, positioning accuracy, management authority and relevant management regulations of the company. Table 2.2 only roughly classifies the dangers of obstacles and provides an idea to solve the complex environmental modeling problem of electronic charts, which can be appropriately adjusted according to the actual above conditions in the modeling process. Meanwhile, if setting $\lambda < 0.01$, even under the same β parameter setting conditions above, it will maintain a greater safe distance with the obstacle, and setting the $\lambda > 0.01$, safety distance will decrease, see Table 2. 3.

Table 2. 3 Limit range (n mile) between OS and a point obstacle at different λ and β

β	λ=0.1	λ=0.01	λ=0.005	λ=0.001
0.2	3.39	4.80	5.15	5.88
0.5	2.15	3.03	3.26	3.72
1	1.52	2.15	2.30	2.63
5	0.68	0.96	1.03	1.18
10	0.48	0.68	0.73	0.83
20	0.34	0.48	0.51	0.59
50	0.21	0.30	0.33	0.37
100	0.15	0.21	0.23	0.26
500	0.07	0.10	0.10	0.12

Source：吕红光, & 尹勇. (2019). 基于电子海图矢量数据建模的无人船路径规划. *交通信息与安全, 37*(05), 94-106.

Moreover, if the distance between multiple obstacles is close, the superimposed potential field will occur, thus increasing the risk of the water, which is consistent with the actual navigation, such as the passage of dangerous objects on the left and right, especially for coral reef waters. Therefore, the safe distance should generally be determined according to the scale of the unmanned ship, and then the appropriate λ and β, are calculated to determine the navigable waters and dangerous waters.

2.2.2 Line and face shaped potential field

The potential field equation $c=\varphi(p)$ is defined by the generalized Sigmoid function (Ren, McIsaac, Patel, & Peters, 2007)

$$f_{\text{line}}(c)=\frac{1}{1+e^{-\gamma\bullet c}} \tag{2.3}$$

Where γ is a positive adjustable parameter, similar to β, can adjust its range of influence according to the risk of the obstacle. Note that in the actual modeling process, the coding direction of the line is the counterclockwise direction. When $c=0$, point p is in the line of $\varphi(p)=0$, potential field value of point p is 0.5; when $c>0$, point p is inside the line (left), the potential field value is to 1; when $c<0$, point p is outside the line (right), the potential field is small and gradually tends to 0.

Similar to point obstacles, more contents about modeling methods of line and face obstacles can be referred to (吕红光 & 尹勇, 2019). Using this modeling method, the corresponding potential field parameters according to the different attributes of line and face obstacles can be set up, so as to establish the relationship between the potential field function and the safe distance that should be maintained with the obstacles. An example of the first modeling method for face obstacles is as follows：

Any facial element barrier can be composed of N lines $c=\varphi_j(p)$ intersection whose potential field can be represented as the product of the Sigmoid functions of these lines or curves (positive integer j from 1 to N).

$$f_{face}(p)=\prod_{j=1}^{N} f_{\text{curve}}(\varphi_j(p)) \tag{2.4}$$

As shown in Figure 2. 3, a total N line from φ_1 to φ_n includes a curve such as φ_5, in a counterclockwise direction, and then a surface element potential field with a high potential field value can be formed on its left side.

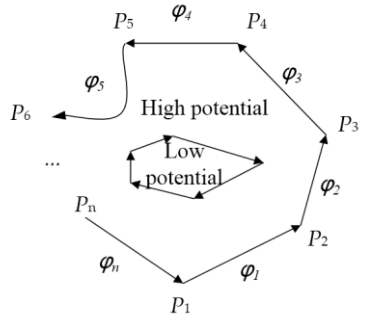


Figure 2. 3 Construct diagram for potential field of face or surface elements

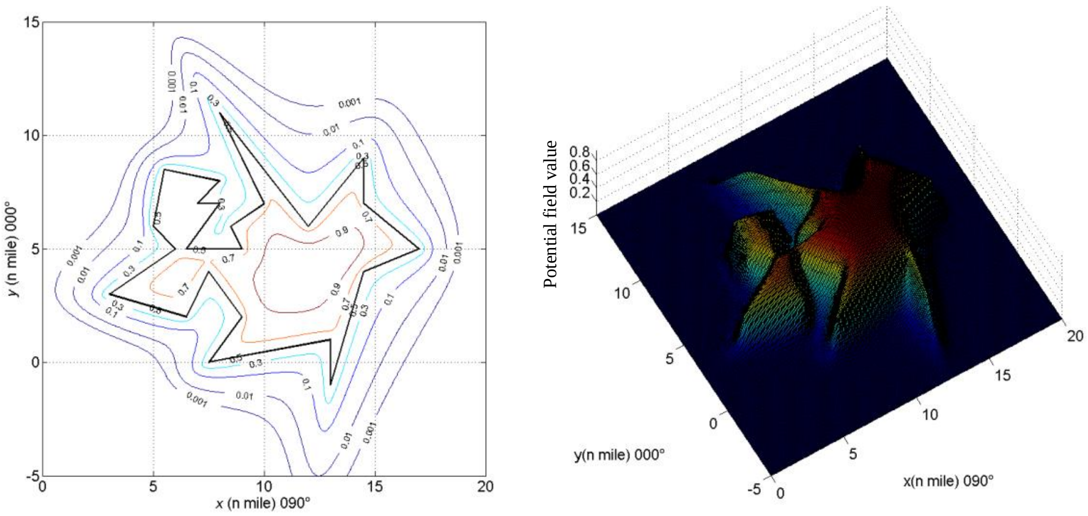
However, this modeling method of surface obstacle potential field is very complicated and needs to be improved here. First, this approach is useful in utilization in ECDIS because all face obstacles, can be approximately considered as some connections of discrete points, which are readily accessible in electronic charts. Then it needs to construct arbitrary polygons using these points of obstacles or depth contours and then form the potential field of them. According to the author's prior work (吕红光 & 尹勇, 2019), a convex polygon composed entirely of straight lines is very easily constructed by formula (2.4). However, for a concave polygon, it cannot be constructed by the above method, except using a curve instead of the concave part of the edge. Thus another method adopted in this paper is to perform convex decomposition of the concave polygon and forms the implicit function of the concave polygon. By substituting the function of this polygon representation into formula (2.3) to construct the potential field $f_{\text{face}}(\varphi(p))$ of an irregular obstacle.

Figure 2. 4 and Figure 2. 5 are maps of a concave obstacle potential field composed of γ =1 and γ =5, respectively. The potential field of the concave obstacle also meet the rules “the smaller the γ, the larger of the potential field influence range”. It should be emphasized that these polygons can be constructed with multiple lines. This is very suitable to construct the potential field of any obstacle in ECDIS platform. Because discrete coordinate points can be conveniently read to describe various lines.

For example, a series of point of the face-shaped concave obstacle in Figure 2. 4 and Figure 2. 5, are shown in Table 2. 4.

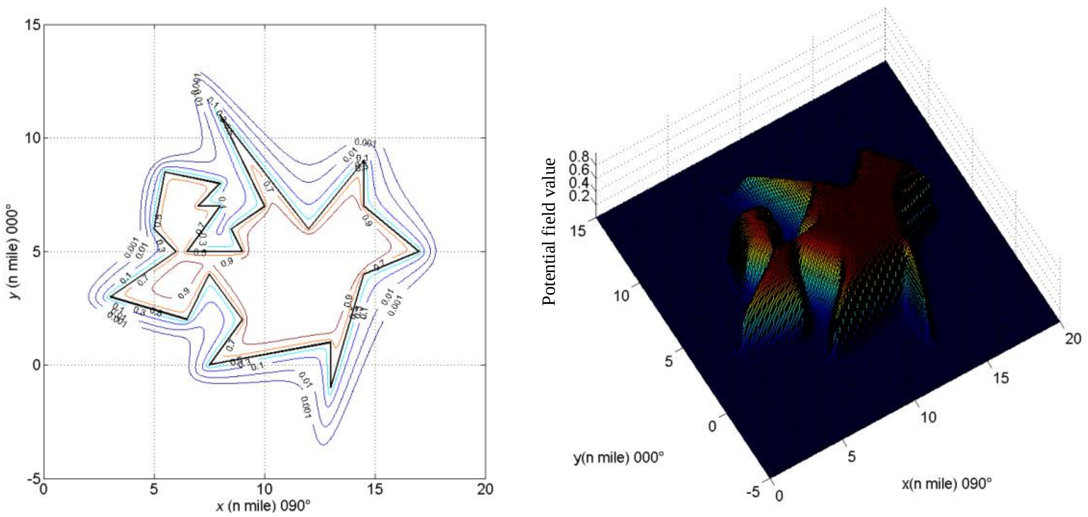
Table 2. 4 Coordinate of the points in the concave obstacle

No.	x- ordinate	y- ordinate
1	3	3
2	6.5	2
3	7.5	4
4	9	2
5	7.5	0
6	13	1
7	13	-1
8	14.5	4
9	17	5
10	14.5	7
11	14.5	9
12	12	6
13	8	11
14	10	7
15	8.5	6
16	9	5
17	6.5	5
18	8	7
19	7	7
20	8	8
21	5.5	8.5
22	5	6
23	6	5



a) equipotential range diagram b) potential field surface diagram

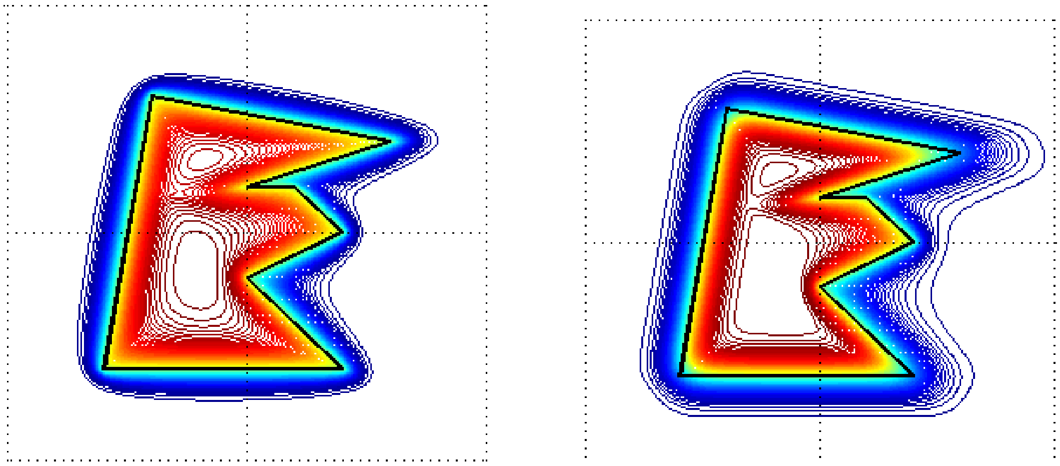
Figure 2. 4 Potential contours and surface of face obstacle for γ=1



a) equipotential range diagram b) potential field surface diagram

Figure 2. 5 Potential contours and surface of face obstacle for γ=5

Considering that obtaining the implicit function of very complex concave polygons is challenging, the method of formula (2.4) is very simple and efficient in some cases, and the potential field between the two methods is not large, as shown in Figure 2. 6. Therefore, the operator can choose one of modeling methods according to the actual situation.



a) equipotential diagram by the formula (2.4) b) equipotential diagram by the implicit function

Figure 2. 6 Potential contours of face obstacle using two methods

If there are M points and surface elements, the respective formed potential fields are added to form the final potential field. If some of the potential fields overlap then the potential is strengthen. The general expression for the potential field formed by various obstacles in the environment is:

$$f(p)=\sum_{i=1}^{M}(f_{\text{face}}(\varphi(p))+f_{\text{point}}(p)) \tag{2.5}$$

Where $\varphi(p)$ represents the implicit equation of the face obstacle.

The point, line and surface obstacles are classified by risk level according to their properties, to determine the minimum safe distance between the ship and them. Through the setting of the safety potential field λ, and parameters β and γ, the offline potential field of the navigation environment can be constructed according to the above method.

For the very complex navigation environment, it is recommended to use a computer with good computational ability to establish the potential field of the environment in advance, and apply the potential field map directly during the collision avoidance or path planning process.

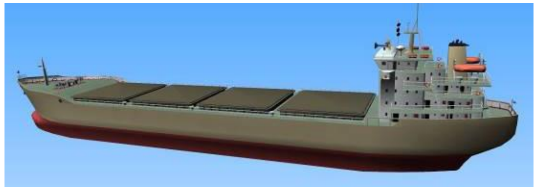
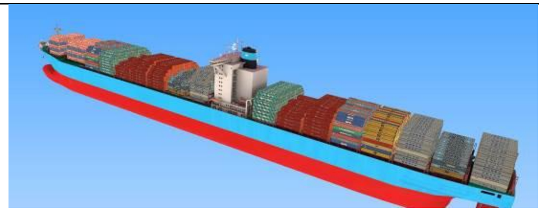
2.3 Modeling of ship' dynamics

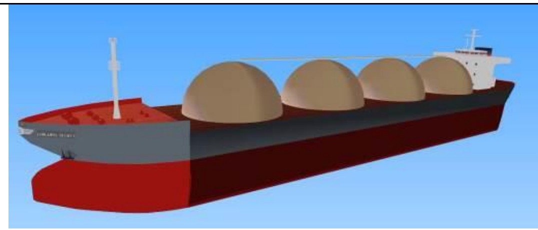
In order to suit the application in the actual environment for the proposed CA decision-making method, the dissertation adopts more accurate ship's dynamics model with 6 degrees of freedom in the ship simulator, with various ship types and tonnage, and the simulator itself has an automatic rudder module, using a more advanced control algorithm, not limited to PID (Proportion Integration Differentiation) and PD (Proportion Differentiation) control. The performance of the ship motion mathematical model is as follows:

- The model has ship navigation and handling performance, showing all handling of the ship at low speed, water depth conditions (shallow, narrow channel and offshore), various wind and currents;
- The model includes the full, half and ballast load states of the ship, and can be adjusted as required;
- The model covers various types of common ship types with different tonnage, and the accuracy error of the typical parameters with the prototype ship is less than 20%, and the key ship type error is less than 10%;
- The model can reflect the shore effect, shallow water effect, inter-ship effect and other effects.

Table 2. 5 shows several typical examples of the ship dynamics models established in our laboratory full task maneuvering simulator, including the basic parameters and 3D graphics of various ships.

Table 2. 5 Various ship mathematical models in Ship Simulator

No.	**name**	**type**	**load condition full (F) ballast (B)**	**LOA(m)**	**breadth (m)**	**draft (m)**	**displacement (T)**	**speed (kn)**	**3-D view**
1	NingAn	Bulk	F	184	32	9.5	44549	10.69	
2	NingAn	Bulk	B	184	32	5	22345	11.74	
3	YinHe	Container	F	168	28.4	9.5	28145	18.1	
4	YinHe	Container	B	168	28.4	7.5	21129	18.78	
5	6600TEU	Container	F	347	43	14.5	120744	24.5	
6	6600TEU	Container	B	347	43	9	73235.9	24.5	
7	ZiLuoLan	Passenger	F	130	17.6	6	7440	14.28	
8	ZiLuoLan	Passenger	B	130	17.6	5.2	6040	14.28	

No.	name	type	load condition full (F) ballast (B)	LOA(m)	breadth (m)	draft (m)	displacement (T)	speed (kn)	3-D view
9	TianE	RoRo	F	120	20.5	5.7	7286	14.08	
10	TianE	RoRo	B	120	20.5	3.7	4323	14.28	
11	VLCC32	Tanker	F	334	58	20.8	308838	14.36	
12	VLCC32	Tanker	B	334	58	11.6	168655	14.98	
13	Primorye	Tanker	F	247.8	42	13.6	111509	14	
14	Primorye	Tanker	B	247.8	42	8	62643.8	17	
15	LNG-1	LNG	F	292	43.35	11.5	99997.9	19	
16	LNG-1	LNG	B	292	43.35	6.3	53336.4	19	

Apply the low-order PD controller on the above ship model to provide a new course to the collision avoidance decision, and integrate the controller into each step of the collision avoidance decision algorithm, make full use of the new parameters after the decision, such as the actual course and position, to ensure that the collision avoidance or path planning is more consistent with the actual ship and simulate in the software environment.

$$\delta = -K_p(\psi - \psi_{desired}) + K_d r \qquad (2.6)$$

where δ is rudder angle control input variable, K_p is proportional constant and K_d is differential constant. ψ is the immediate heading, ψ_{desired} is the collision avoidance heading required by the algorithm, and r is the yaw rate.

3 DETERMINATION OF COLLISION RISK

To judge whether there is a collision risk between ships, the safety distance between own ship (OS) and target ship (TS) is generally selected as the main index, and also the encounter situation at that time and the requirements of COLREGs are considered.

3.1 Safe distance between ships

The safe distance required between the ships varies dynamically. There are many factors affecting the safety distance, including the ship type, scale and maneuvering performance of OS and TSs, the relative speed of the two ships, water area types (including traffic density), natural and hydrological and meteorological conditions, and ship's position credibility, as well as the technical level, knowledge and experience of the crew (Pietrzykowski, 2008).

First, to solve the problem with convenience and leave some room for safety, the OS and TS were enlarged into a circle, as shown in Figure 3. 1. The circle was centered on the positions of OS and TS (i.e. $\boldsymbol{p}_{os}$ and $\boldsymbol{p}_{ts}$ respectively), capable of containing LOA of the ships and leaving sufficient safety margin (sm_{os} and sm_{ts}), where v_{os} and v_{ts} represent the speed of OS and TS respectively. The selection of safety margin should consider the credibility of OS and TS position data, the ship scale effect leads to the increased domain range (翁建军, 2004). The safety margin of the large ship is larger than the small ship, represented by the product of LOA and an adjustable coefficient (μ). μ =2 for the ship of 100,000 tons, but μ =6 for the big ship of 1 000 000 tons (郑中义 & 吴兆麟, 2000). The circle radius of the OS and TS are respectively read as R_{os} and R_{ts}.

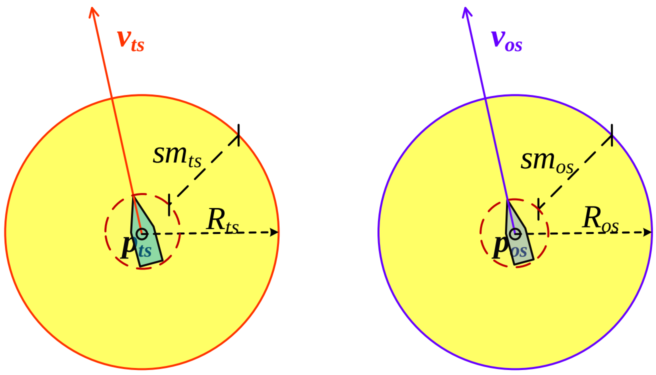


Figure 3. 1 Expanded circles for the TS and OS

Second, the distance between the enlarged circle boundary of OS and TS is expressed by d_{safe}, which is based on the maneuvering performance, their respective speed, relative speed, water area type (including traffic density), hydrometeorology and other conditions. In fact, this distance is also related to the respective course of OS and TS, that is, different d_{safe} in different situations (Pietrzykowski & Uriasz, 2009) but this will undoubtedly increase the complexity of d_{safe}, the use of circular domains can avoid such problems. From the study of Pietrzykowski, it can be seen that the feasibility of the circular domain replacing other irregular domains, and the larger the d_{safe} required by open waters, the closer to the circular domain for the ship (Pietrzykowski & Uriasz, 2009). Thus, the domain radius d_m, determined in this paper is the safe distance between OS and TS, which can be determined by the following formula:

$$d_m = R_{os} + d_{safe} + R_{ts} \tag{3.1}$$

The corresponding domain range of ships centered on the OS is shown in Figure 3. 2, and with OS as the reference point, any TS should also be kept outside the circular domain centered on the OS position and with the d_m as the radius.

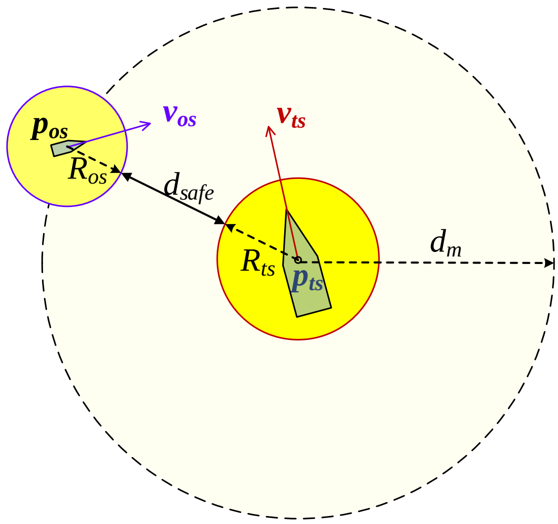


Figure 3. 2 Ship domain centered with the TS position

It should be noted that the OS centered domain is different from the TS centered domain, namely, the d_m value will be different for the TS an OS. This paper studies the behavior of collision avoidance between vessels which shall be deemed as in sight of one another. OS and TS are in the consistent natural environment, and the relative speed of the two ships is the close speed on both sides. From these two aspects, the difference of d_m between them is small. The main reasons for the d_m difference are the factors of ship scale and maneuvering performance.

Since the R_{os} and R_{ts} in formula (3.1) have considered the scale of OS and TSs, while the d_{safe} considers the maneuvering performance and relative speed of both ships. The ship with poor handling performance caused greater collision avoidance pressure to the TS, relatively high speed, the rapid approach of the two ships will also lead to the increase of collision avoidance pressure. Therefore, the domain centered on the TS is the need to consider the relative speed of the two ships and apply them to the determination of d_{safe}.

The value of the d_{safe} can be determined by the superposition effects of multiple conditions listed in Table 3. 1. If the ship has poor maneuvering ability and high relative speed (fast approaching), poor visibility, and large wind and waves, these impacts are superimposed (N. Wang, 2012), the required d_{safe} will be larger, and otherwise the d_{safe} value is small. Unlike the other nature of the conditions is the "sailing waters," which is a special and determinant. When sailing in open waters, d_{safe} may be determined by the above conditions, but in narrow waters and reef areas, the value of d_{safe} will be decisively affected by the range of navigable waters and the allowable spacing from static obstacles. And in narrow waters, ships are generally maneuvered, with better maneuverability, and the required d_{safe} is relatively small.

Table 3. 1 The determining factors of the d_{safe}

items	features	d_{safe}	coefficient
advance distance (A_d)	big A_d, low maneuvering performance	big	$\frac{time\ step(\text{h})\times T_{90}(\text{s})}{1852}$
The relative speed of OS and TS close to each other $\lvert \boldsymbol{v}_r \rvert$	big，fast approaching	big	*time step* (h)
	small, slowly approaching	small	
water area：d_{water}	no restricted maneuvering open water	big	1
	restricted maneuvering, or narrow water	small	0
natural conditions including the safe distance determined by hydrological and meteorological condition：d_{nature}	good weather, during the day, good visibility, little wind and wave	small	0
	bad weather, night, poor visibility, strong wind and wave	big	1

Source: 吕红光. (2019). *基于电子海图的多船避碰决策及路径规划研究*. 大连海事大学

By the above analyses to determine the unified d_{safe} standard of OS and TS, this is a simple and easy method to implement, as follows(吕红光, 2019):

$$d_{safe} = time\ step\lvert \boldsymbol{v}_r \rvert + \frac{time\ step \times T_{90} \times A_d}{1852} + \mu_w d_{water} + \mu_n d_{nature} \tag{3.2}$$

Where:

time step is a sampling cycle or sampling time in h;

$|\boldsymbol{v}_r|$ is the absolute value of the relative speed that OS and TS approaches to each other, in kn;

T_{90} is the time in seconds used when the course changes 90 ° at a full speed for the ship with poor maneuvering ability;

A_d refers to the advance distance of a ship with poor maneuvering ability, that is, the longitudinal movement distance of the ship center when the heading changes 90 °, the advance of general ship is 2.8~4 times LOA (洪碧光, 2016), unit in meter;

d_{nature} and d_{water} are the safety distance for different natural conditions and the water requirements, which can be adjusted according to the actual natural conditions and traffic density, the default value is 0.5 n mile;

μ_n and μ_w is coefficients of d_{nature} and d_{water}, respectively, which can be set 0 minimum and 1 maximum.

For example, the time step=15s represented by 1/240 h, $|\boldsymbol{v}_r|$=40 kn, T_{90}=255s for a ship with poor maneuvering ability, A_d=1100m, at day, good visibility, small wind and waves, the μ_n=0 will be set. For unrestricted open waters, μ_w=1, then d_{safe}=1.3 n mile. In narrow waters, μ_w=0, take the value if the sum of the other three is less than 0.5 n mile; if greater than 0.5, the value is set to 0.5 n mile. In some special cases, if ship dynamics is unknown, d_{safe} can also be set up, or by default of 0.5 n mile in order to easily observe the collision avoidance effect.

3.2 Judgment of Situation and collision risk

In open waters, if a collision occurs, the process generally consists of the following stages: no collision hazard at large distance with the OS, risk of collision, close quarters situation, immediate danger to the final collision (孙立成, 2000). This is a stage representation of the development of the distance between the two ships. The purpose of collision avoidance decision-making algorithm is to prevent collision and actively to avoid urgent situation or dangers.

First, the algorithm should be able to make regular collision avoidance decisions according to the rules and the customary practice of seafarers. Secondly, the algorithm should also have the ability to avoid emergency, such as: when a TS is not according to the rules, or her avoidance action does not conform to the rules, or with the OS uncoordinated CA actions, or the two ships for whatever reason is close to each other, CA decision algorithm should also be able to take the corresponding most helpful CA action. Therefore, the CA decision is analyzed based on two modules: cooperative collision avoidance and emergency collision avoidance.

3. 2. 1 **Regular collision avoidance**

Collision risk refers to the hazard that the two ships cannot pass clear at the set safe distance d_m at a certain length of time when they following the current course and speed without changing. When the two ships were very long apart, it took a long time before a collision could occur. Under such circumstances, it cannot be concluded that the two ships were in danger of collision and immediately needed to take action to avoid the collision. If the action is taken prematurely, such action may be blind, ineffective or even detrimental to the development of the later situation. Therefore, in determining the risk of collision and whether to avoid collision action, other factors should be taken into account, especially the distance between the two ships. Under the current framework of the Rules, it generally refers to "the distance when they are in sight of one another", i.e. the distance at which the give-way ship can take action to avoid collision after the situation is determined. Section 11 of the COLREGs Rule 3 states that "Vessels shall be deemed to be in sight of one another only when one can be observed visually from the other". This is a practice for "manned ships" and generally references the visible distance of the sidelights and mast lights. Therefore, the opportunity of the collision avoidance action in the algorithm is quantified as a distance.

The determination of d_m in the algorithm is different from the traditional DCPA that simply treating two ships as points (without considering the ship scale and other influencing factors) and calculating the distance between the two points, but fully considers the impact of the domain model and various factors on the safe distance.

Therefore, the judgment of collision risk in the paper considers the urgency of time and space, combines it with the Rules, and decomposes into two important conditions (Hongguang Lyu & Yin, 2019):

① Checking Criterion of Collision Risk (CC): If the OS is steering at current course and at current position, she shall not pass clear of the TS at the safe distance d_m.

② Checking Distance of Collision Risk (CD): When the distance between the OS gets CD and meets the CC conditions, the OS should take CA action, if obstacles are outside CD, no need to take CA action.

When determining *CD* based on the domain radius d_m, it should be assumed that the obstacle or TS can produce the repulsion field affecting the OS, and the influence radius is noted as ρ_o ($\rho_o > 0$) ,which is set by the operator considering the following factors:

- ρ_o is generally large in open water, limited visibility and other conditions;
- Considering the opportunity of taking CA action at different encourter situations, for the overtaking situation the OS can take action at near 3 n mile, and the crossing and head-on situations the OS can take action at 5~6 n mile. So it needs to set a minimum ρ_o value for different situations, which is noted as ρ_{omin}. Then based on the navigation practice, it is

suggested that the ρ_{omin}=3 n mile and ρ_{omin}=5 n mile are selected at ovtertaking situation and the other situation, respectively.

- Some regional static obstacles are very large even exceeds 3 n mile, leads to a large range of influence for the repulsive field. For this situation, ρ_o is set to a very small fixed value, will lead to collision with the large obstacle, so ρ_o should be automatically adjusted along with the size of the obstacle.

Therefore, in the paper, *CD* is defined as the sum of d_m and ρ_o, and ρ_o takes the maximum value of the two: f_k times of radius of obstacle bulge circle and ρ_{omin}:

$$\begin{cases} CD = d_m + \rho_o \\ \rho_o = \max\ (fk \times R_{ts},\ \rho_{omin}) \end{cases} \tag{3.3}$$

Where f_k is a positive proportional coefficient, called the distance influence factor of obstacle. When the distance between the OS and TS, i.e. $d=\rho(\boldsymbol{p}_{os},\boldsymbol{p}_{ts})$ is less than or equal to *CD*, the algorithm determines whether the CC condition is met. In Figure 3. 3, the OS and TS approach each other at positions p_{os} and p_{ts} (O and T) at the speeds v_{os} and v_{ts} respectively. If the extended line of the relative speed $\boldsymbol{v}_{ot}$ ($\boldsymbol{v}_{ot}$=$\boldsymbol{v}_{os}$-$\boldsymbol{v}_{ts}$) placed in the domain with the center of position T and the ridius d_m of circle, the two ships could not pass over a safe distance d_m, then there is the risk of collision for the two ships.

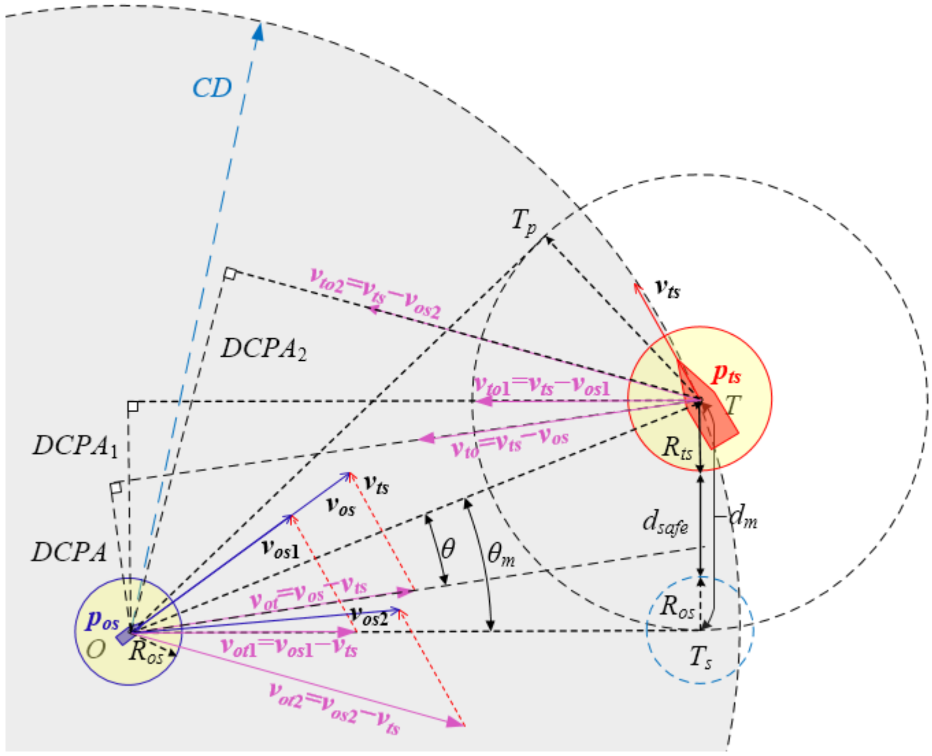


Figure 3. 3 Regular collision avoidance module

The boundary conditions of the CC can be determined in Figure 3. 3, for the tangent line of O to the domain circle of TS, the left cutting point of the $\boldsymbol{OT}$ is read as T_p, the right cutting point of the $\boldsymbol{OT}$ is read as T_s. When the v_{ot} extension line fell beyond $\angle T_pOT_s$, the OS and TS could pass at a safe distance greater than or equal to d_m. Let the angle between $\boldsymbol{v}_{ot}$ and $\boldsymbol{OT}$ be θ (θ>0) and the angle between tangent $\boldsymbol{OT}_s$ (or $\boldsymbol{OT}_p$) and $\boldsymbol{OT}$ be "maximum angle of relative position line" θ_m (θ_m>0), θ_m can be determined by the following formula:

$$\theta_{\mathrm{m}} = \arctan\left(\frac{d_m}{\sqrt{\rho^2(\boldsymbol{p}_{os}, \boldsymbol{p}_{ts}) - d_m{}^2}}\right) \tag{3.4}$$

Note that when $\theta<\theta_m$, the corresponding $DCPA$ is less than the safe distance d_m. Therefore, the collision risk detection standard CC is summarized as:

$$\theta<\theta_m \tag{3.5}$$

It should also be noted that at the distance $d \le d_m$ from the OS the TS, it no longer needs to draw the tangent line to the domain circle of the TS through the position O of the OS, i.e. the θ_m cannot be found in this case, since OS was already in the domain of the TS (or TS in the domain of OS). Therefore, the conditions for identifying the collision risk are:

$$\begin{cases} d_m < d \le CD \\ \theta < \theta_m \end{cases} \tag{3.6}$$

When this condition is established, the collision avoidance (CA) decision-making shall be taken. Assuming a speed reduction CA strategy is selected, when the OS slows to $\boldsymbol{v}_{os1}$, the extension line of relative speed $\boldsymbol{v}_{ot1}$ is just over the cutting point T_s, then $\theta = \theta_m$. In this condition, it deemed that the two ships can pass safely, meeting $DCPA_1 = d_m$. But considering the practical CA measures for open water, altering course may be preferred. The algorithm is designed to make course alteration, and meet the requirements of good seamanship and the COLREGs, and turn right at least 30 °. Assuming that after turning the new course of OS is $\boldsymbol{v}_{os2}$, and the extension line of relative speed $\boldsymbol{v}_{ot2}$ falls on the right side of the tangent OTs, then the OS and TS can pass at a safe distance more than d_m, namely $DCPA_2$.

3.2.2 Emergency collision avoidance

If the OS encounters many TSs in a complex situation, or encounters the uncooperative TS, there may be exist a situation when the distance between TS and OS is close to d_m or less than d_m. Here the taken CA operation is called emergency CA action, and the decision-making conditions are shown in Figure 3. 4.

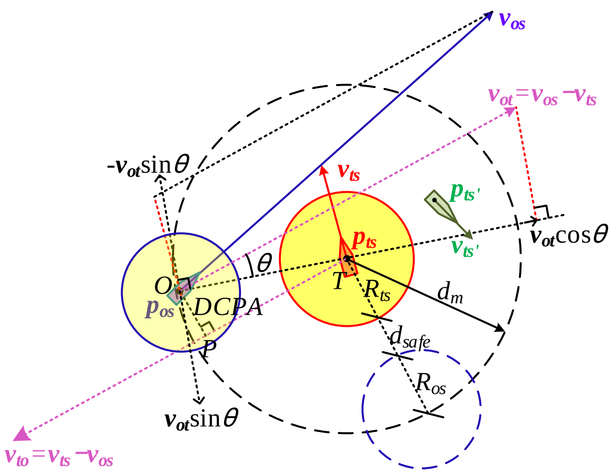


Figure 3. 4 Emergency collision avoidance module

Source: Lyu, H., & Yin, Y. (2018). Fast Path Planning for Autonomous Ships in Restricted Waters. *Applied Sciences, 8*(12).

According to the above, one of the conditions: $\theta<\theta_m$ for negotiating collision avoidance no longer applies in this case. So in addition to the distance judgement $d\leq d_m$, the *DCPA* and *TCPA* should be considered. Without consideration, it would lead OS to take CA action against the TS at $\boldsymbol{p}_{ts'}$ .However, in fact, there was no danger of collision between the TS and OS. Accurate *TCPA* and *DCPA* require accurate perception of the TS position, size and dynamics. This dissertation assumes that the relevant sensor on board gets accurate data at close range, and in Figure 3. 4, the *DCPA* and *TCPA* at the position *O* of the *OS* are calculated as follows:

$$\begin{cases} DCPA = OP \\ TCPA = \dfrac{PT}{|\boldsymbol{v}_{to}|} = \dfrac{PT}{|\boldsymbol{v}_{ts} - \boldsymbol{v}_{os}|} \end{cases} \tag{3.7}$$

Where $TCPA \geq 0$, $\boldsymbol{v}_{to}$ is the relative speed for TS to OS. The operator can configure the threshold values D_A and T_A (Hilgert & Baldauf, 1997) corresponding *DCPA* and *TCPA* according to maneuvering performance of the ship, ship size and visibility at the time. Once the measured *DCPA* and *TCPA* are less than or equal to the set threshold, the most helpful CA action shall be taken, so the criterion for emergency collision avoidance may be written as (Hongguang Lyu & Yin, 2018):

$$\begin{cases} d \le d_m \\ DCPA \le D_A,\ 0 \le TCPA \le T_A \end{cases} \tag{3.8}$$

4 DECISION-MAKING FOR COLLISION AVOIDANCE AND PATH PLANNING

Path planning of unmanned ship includes the avoidance of various static obstacles, also includes automatic avoidance of various dynamic TSs under the COLREGs constraints. And doing this should guarantee that avoidance actions with dynamic TS will not lead to a collision with a static obstacle and eventually arrive at the near waypoint or destination. So the path planning of unmanned ships is a combination of dynamic and static planning, and a combination of global offline and online planning.

4.1 Path planning in a static environment

According to the above environment modeling method in chapter 2, path planning algorithm is designed for irregular static obstacles. Unmanned ships navigate within the sea without getting too close to static obstacles. Therefore, the safety potential field threshold value λ. e.g. a very small value λ=0.001 can be set according to the safety level of the unmanned ship, maneuvering performance and cargo conditions, etc. As shown in Figure 4. 1, on the surface obstacle boundary, its potential field value is λ, the potential field value of internal boundary is more than λ, but for the external boundary the potential field value is less than λ. The potential field values of OS's subsequent positions all are less than the λ, can ensure that the OS doesn't cross the static barrier zone or maintain a safe distance from it.

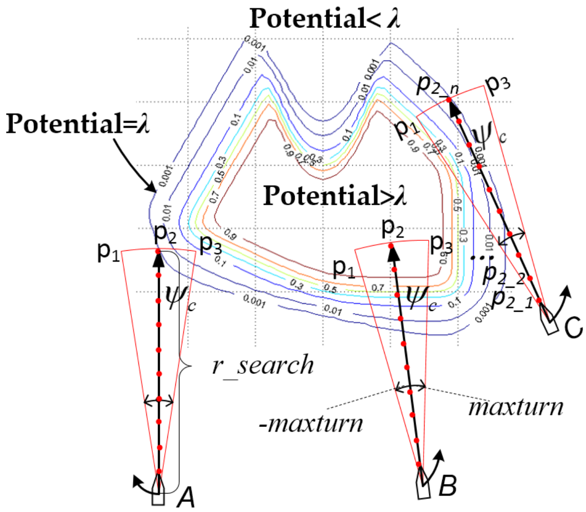


Figure 4. 1 Course alteration determined by the minimum potential following method

For example, the mariner ship type turns 90° under 35° rudder angle in the interval of 150s (林晓杰, 2015). In order to get more safe operation allowance, the OS should take CA action in advance, rarely using full rudder steering in practice. Selecting *time step*=15s let the maximum steering degree of the OS be *maxturn*=5°. As shown in Figure 4. 1, calculate the potential field value $f(p_2)$ at the current position, such as A and B, adjusting the detection distance *r_search*. If the $f(p_2)\geq\lambda$, the ψ_c has a collision hazard with the static obstacles, it is necessary to alter course. At both directions of the OS course "$\psi_c -$ *maxturn*" and "$\psi_c -$*maxturn*", of which the potential of *r_search* ends p_1 and p_3 were $f(p_1)$ and $f(p_3)$, respectively. The p_1 and p_3 are unified writing to p_w, then to choose the suitable w^* corresponding to the minimum potential value $f(p_w)^*$. By doing this to determine the optimized steering direction of OS to avoid static obstacles.

$$w^* = \arg_{\mathbf{w}\in\{1,3\}}\min\{f(p_w)\} \qquad (4.1)$$

As shown in Figure 4. 1, the OS's next CA action is turning left at position *A* and right at position *B*. If $f(p_1)=f(p_3)$ is true, the algorithm defaults to right turn of the OS. Note that during steering and advance, once the $f(p_2)<\lambda$, such as position *C*, it would be considered no danger in front of OS, making the OS through the danger. To avoid this risk, this paper improves the preliminary algorithm (Hongguang Lyu & Yin, 2018), makes *n* equidivides of *r_search* at ψ_c direction according to the obstacle characteristic. It should be noted that the length of each part should be less than the range of the obstacle potential field. For example, it should satisfy the following formula:

$$\exists p_{2\_k}(k \in 1,2,3...n),\ f(p_{2\_k}) \geq \lambda \qquad (4.2)$$

The algorithm adopts formula (4.2) and its subsequent method to avoid avoidance. For example, at the position *C*, the OS should continue to turn right until all the p_{2_k}s in front of the OS meet the conditions of $f(p_{2\_k}) < \lambda$, and then use the CA decision-making algorithm in the dynamic environment to determine the new course and path of the OS.

4.2 Automatic CA decision making in dynamic and complex environments

The movement of OS is non-linear, so the assumption that my ship speed is constant, may make the path planned by the algorithm difficult to apply in practice, so the following factors should be considered.

(1) Steering time, speed reduction and turning performance

Some algorithms assume the ship sails (Lazarowska, 2017) at constant speed, without considering the above factors. If the ideal algorithm is applied to practice, there are errors in the time and position of the points where the CA operation are executed actually and in the algorithm. First, the steering opportunity determined by the algorithm is performed immediately, but delayed at the actual execution. Second, when the ship turns, due to speed reduction, the position of the vessel during the steering will gradually lag behind the position of the ship determined in the algorithm. Third, in practice, due to inertia, steering opportunity, turning performance, etc., the ship is impossible to turn to a new course immediately. For example, some large right-handed screw ships begin to turn after 15 s if steering rudder angle 10°. So it is difficult to make the ship turning instantly at the above time. This factor is not considered in the general algorithm, which may lead to a greater deviation between the planning position and the actual navigation. The above points may lead to the failure of the algorithm planning path or the excessive error in the actual application. In complex waters, this may directly lead to the distance from TS being less than the minimum safety value and thus in danger.

(2) The influence of winds, seas and currents

Affected by natural conditions, ships are difficult to maintain a constant speed. The algorithm considering the mathematical model of ship also can plan path with the disturbance conditions such as winds, seas and currents (林晓杰, 2015). During the operation, the influence of winds, seas and currents can be embedded in the mathematical model of ship dynamics, and then, the CA strategy under this condition can be solved.

(3) Changing environment and continuous update of CA strategy

Sailing in complex waters, TSs movement is complex and unpredictable to predict. The results of offline planning cannot be used directly for dynamically unknown environments. Therefore, the automatic CA algorithm should be able to respond quickly to the status change of TSs, adjust the collision avoidance strategy in time, and calculate the new CA strategy according to the mathematical model and control algorithm of the OS, and then calculate the new CA strategy. Therefore, the CA strategy planned by the algorithm should be continuously updated.

Using the improved Artificial Potential Field (APF) method in (H. Lyu & Yin; Hongguang Lyu & Yin, 2018, 2019), the paper constructs the gravitational potential field U_{att} and repulsion potential field U_{rep}, and then obtains the negative gradient of them, to obtain the corresponding gravitational force $\boldsymbol{F_{att}}$ and repulsion force $\boldsymbol{F_{rep}}$. The difference is retaining only the normal CA module of repulsive force $\boldsymbol{F_{rd}}$ of the dynamic TS, and emergency CA module of repulsion $\boldsymbol{F_{re}}$, and improve the applicable conditions of emergency CA module, see formula (4.3)

$$\boldsymbol{F_{rep}}(p,v)=\begin{cases}\boldsymbol{F_{rd1}}+\boldsymbol{F_{rd2}}+\boldsymbol{F_{rd3}}, & d_m < d \le CR \text{ and } \theta < \theta_{\mathrm{m}} \\ \boldsymbol{F_{re1}}+\boldsymbol{F_{re2}}+\boldsymbol{F_{re3}}, & d \le d_m, d_{CPA} \le 0.3 \text{ n mile and } t_{CPA} \le 6\,\text{min} \\ \text{not defined}, & \text{other situations}\end{cases} \tag{4.3}$$

In the formula, the direction and action of each force are shown in Table 4. 1. Take the repulsive force in the normal CA module as an example. As shown in Figure 4. 2, finally, the OS is affected by the resultant $\boldsymbol{F_{rd}}$, which can avoid collision with TSs and move towards the goal.

Table 4. 1 Direction and action of the components of the repulsive force

module	**components of $\boldsymbol{F_{rep}}$**	**direction**	**function**
regular CA	$\boldsymbol{F_{rd1}}$	$p_{ts}\rightarrow p_{os}$	make OS stay far away from TS
	$\boldsymbol{F_{rd2}}$	$\perp \boldsymbol{F_{rd1}}$ to starboard	to turn right based on COLREGs and good seamanship
	$\boldsymbol{F_{rd3}}$	$p_{os}\rightarrow$goal	OS towards the goal
emergency CA	$\boldsymbol{F_{re1}}$	$p_{ts}\rightarrow p_{os}$	make OS stay far away from TS
	$\boldsymbol{F_{re2}}$	$\perp \boldsymbol{F_{re1}}$	turn left/right depends on the vector $\boldsymbol{V_{os}}-\boldsymbol{V_{ts}}$ locating which side of $\boldsymbol{p_{os}p_{ts}}$
	$\boldsymbol{F_{re3}}$	$p_{os}\rightarrow$goal	make OS close to the goal

Source: Lyu, H., & Yin, Y. (2018). Fast Path Planning for Autonomous Ships in Restricted Waters. *Applied Sciences, 8*(12).

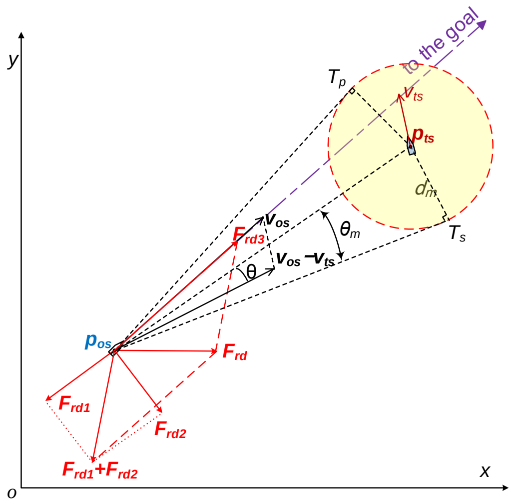


Figure 4. 2 Modified repulsive forces for a dynamic TS

4.3 Hybrid path planning Algorithm

Complex waters limited by regulatory regulations, have numerous static obstacles and limited navigable waters, which affects the automatic passage planning and collision avoidance strategies of MASS. Passage planning is related to the automatic CA decision-making algorithm, so the automatic CA decision-making algorithm should be based on the idea of "offline passage planning" + and "dynamic path planning", mainly manifested as follows:

(1) MASS shall be able to use the results of the offline planning for static obstacles, such as the routes designed by the bridge team, the meteorological route adopted by the company, or the established liner, namely link the waypoints automatically and complete the long distance path planning;

(2) MASS can make dynamic adjustment at any time during the navigation of the offline path planning, including handling the dynamic collision constrained by the COLREGs, and considering the influence of static obstacles. Because the ship needs to deviate from course inevitably, it needs to re-detect the risk with static obstacles.

(3) MASS has the ability of automatic resumption in the case of no risk with dynamic and static obstacles, at the end of the CA action. That is, to automatically approach the original route, pass each waypoint and finally reach the goal.

Some APF methods overlap the gravitational potential field of the goal and the repulsion potential field of the obstacle (Bayat, Najafi-Nia, & Aliyari, 2018; Singh & Parida), which can avoid static obstacles and overcome certain local minimum problems, but are not suitable for avoiding multiple dynamic objects, as well as path planning for long-distance and multi-waypoints conditions. Because it cannot model the gravity at multiple goals superimposed together with the repulsion potential field. If there are multiple goals, such an APF method will yield multiple low-value potential fields with no sequential order, so the combined potential field is difficult to complete path selection.

In addition, the typical APF method seeks the negative gradient of the potential field, obtains the obstacle repulsion and goal gravity, and determines the collision avoidance path (Ge & Cui, 2002; Hongguang Lyu & Yin, 2019), according to the joint force of these two parts. But the static obstacles applicable to this method are more limited to point obstacles.

In order to apply the algorithm to the model based on electronic chart data, suitable for automatic pilot of MASS in long route, to avoid irregular static obstacles and take into account the COLREGs, the path guided hybrid artificial potential field (PGHAPF) method (Hongguang Lyu & Yin, 2018; 吕红光, 2019) is used in this research.

Based on the integration of mathematical model of ship, prior path guidance and waypoint selection algorithm, the PGHAPF method adopts the gradient-based model for dynamic TSs and potential-based model for static obstacles.

Static potential refers to the potential field formed by various static obstacles, there is no need to obtain the gradient of the static potential field, just need to avoid the region with high potential value. The static potential field has a certain priority, because the static obstacles require taking the initiative action to avoid the collision. The dynamic potential field includes two parts, one is the gravitational potential field of the goal, and the other is the repulsive potential field of the dynamic TSs, which needs to obtain a negative gradient of the potential field to obtain the gravity and the repulsion forces. The dynamic potential field has a subpriority because both the goal and dynamic ships are coordinated in practice.

Global prior paths, namely multiple waypoints in a given order, can meet the long route path planning and collision avoidance, and consider the path optimization and reduce the local minimum impact. With or without TS but in no danger of collision, the OS received the gravitational force $\boldsymbol{F}_{att}$ to steer along the route. When there are TSs and the collision risk with OS, the negative gradient of the potential field $\boldsymbol{F}_{rep}$ should be calculated. At last, by computing the vector sum of $\boldsymbol{F}_{att}$ and $\boldsymbol{F}_{rep}$ can obtain the final resultant force of the OS to alter course:

$$\boldsymbol{F}_{total} = \boldsymbol{F}_{att} + \boldsymbol{F}_{rep} \tag{4.4}$$

Where $\boldsymbol{F}_{rep}$ refers to the repulsive force or the emergency repulsive force of the dynamic TSs. Combining the path planning algorithm in the static environment with the automatic CA algorithm of the dynamic TSs, the global algorithm is designed as follows:

Input: OS initial position, heading and speed; goal position; static obstacle data includes parameters λ,β,γ, TS initial position, heading, speed, etc.; for parameters set by dynamic potential field see the reference (Hongguang Lyu & Yin, 2019).

Output: The OS reaches the goal without any collision with obstacles and TSs

Step 1: Calculate the respective potential fields of static obstacles according to formula (2.5) and superposition to form the overall potential field of complex environment;

Step 2: Calculate the relevant motion parameters of each time step of TS and OS, where the relevant parameters of OS include ψ_c, u, v, δ、r and position P_t (calculated according to the ship model and PD control algorithm);

Step 3: Calculate the attractive force according to the literature (Hongguang Lyu & Yin, 2019), according to the judgment of formula (3.6), judge whether there is the collision risk at position P_t; if it is true, calculate the repulsive force, then find the gravity and repulsion vector sum, take the steering angle $\Delta\psi_{os}$ for next time step for the OS to obtain the new course; if there is no collision risk, continue the original course, and repeat the step 2;

Step 4: Calculate the potential field value $f(p_{2\_k})$ for p_{2_k} ($k \in 1,2,3...n$) according to at the OS current position P_t, current course ψ_c and *r_search* ahead. If formula (4.2) is satisfied, the OS is in or approaching hazardous area of a static obstacle, then calculate the w^* to determine turn left or right.

Step 5: Calculate the OS position P_t at next *time step* and her corresponding $f(p_{2\_k})$ according to step 2, repeat this operation;

Step 6: Keep OS in the direction of potential field optimization w^*, until the formula (4.2) is not satisfied, that is to say there is no threat of static obstacles, continue with step 3;

Step 7: When the immediate position P_t and goal are so close to the range r_g, it deemed as the OS reaches the goal, end.

4.4 Fast pre-calculation of CA decision-making

At present, most ships cannot directly enter the unattended stage, and they still need officers to operate. There are many difficulties for ships to adopt the collision avoidance decision proposed by us directly in practice. Therefore, at this stage, this dissertation develops a fast pre-calculation method for collision avoidance decision-making, so that the watching officers on board can intuitively see that in the current dynamic environment of multi-vessel encounter, the OS has obtained the collision avoidance decision and trajectory in the selected time according to the above collision risk analysis and collision avoidance decision-making method, as shown in Figure 4. 3.

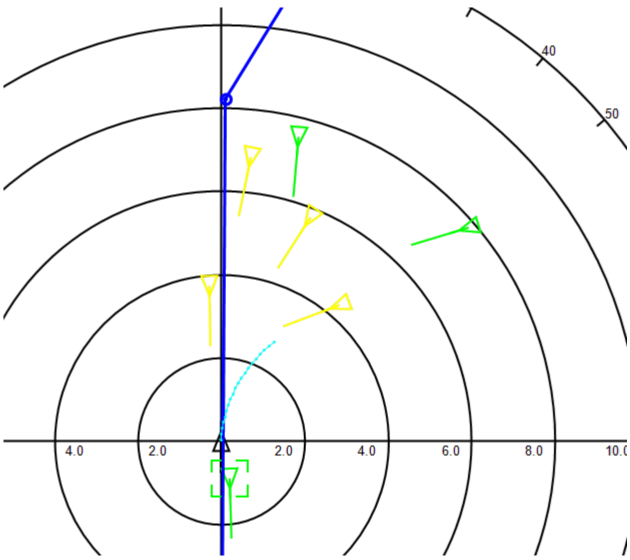


Figure 4. 3 Quick pre calculation for CA assistant decision (diagram 1)

The dissertation selects the next 10 minutes as the time benchmark for fast pre-calculation. Assuming that all other ships maintain course and speed, the OS should choose the course and track (represented by light blue dots) as shown in the figure, so as to avoid the collision risk with other ships. If the course and speed of any TS change, then the OS will calculate the collision avoidance course and trajectory in real time, which is also calculated in the next 10 minutes, see the Figure 4. 4.

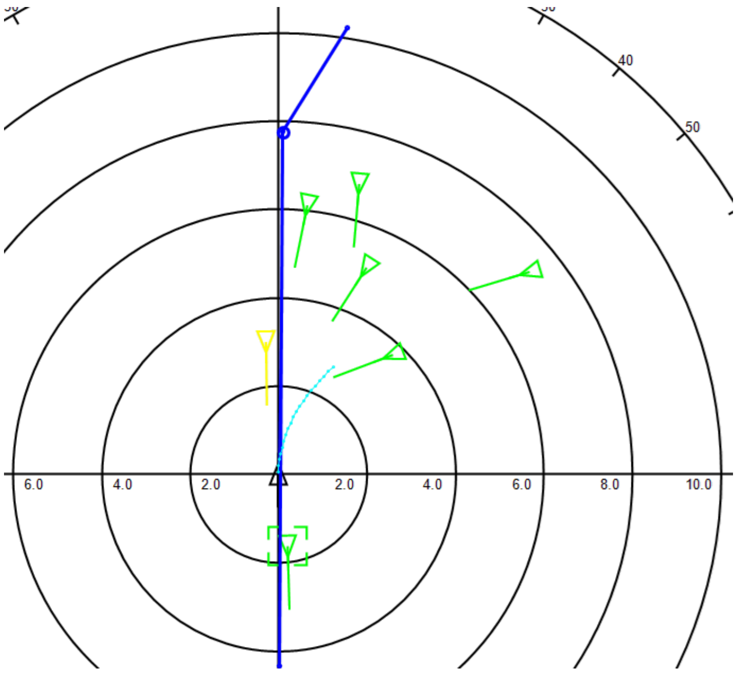


Figure 4. 4 Quick pre calculation for CA assistant decision (diagram 2)

In addition, the blue line in front of the bow in the figure is the planned route of the ship, the yellow ones are the TSs with high collision risk, and the green ones are the ships without collision risk, which can be identified by the watching officers in time.

5 EXPRRIMENT AND DISCUSSION

As for the simulation test of automatic CA decision-making algorithm, most of the previous simulation based on MATLAB platform. This test can directly see the effect of the algorithm, easy to modify and improve the algorithm, and has the advantages of short test time, low cost and low access threshold, but it cannot realistically simulate the geography, hydrology, meteorology and complex traffic environment information of MASS sailing on the sea. Especially, it is difficult to simulate the collision avoidance situation between multiple MASSs and ordinary ships, and it is more difficult to fully verify the applicability of the algorithm to different ship types by using more accurate and various ship type data. However, the test simulation in the full task ship-handling simulator can solve the above problems, so the experiment in this section is carried out in the simulator.

5.1 Introduction of experiment environment

Based on distributed simulation, virtual reality, artificial intelligence and other technologies, the test platform adopts high-precision mathematical model of ship motion, and combines with the hardware equipment of the simulation bridge to build a three-dimensional visual space with multiple visual channels and nearly 360° with immersive perception and ship handling environment.

Figure 5. 1 shows the image of part of the simulation platform, because it has realistic three-dimensional environment scene information, including weather, sea state and other information that can be simulated; With the setting environment of multi autonomous ship (i.e. OS or TS) and target ship (i.e. TS), dynamic target information can be obtained; It is equipped with ECDIS, radar, central control display and other equipment similar to the actual ship. Therefore, the test of

automatic collision avoidance algorithm based on this platform will be very close to the experience and effect of real ship collision avoidance test.

Figure 5. 1 System structure of the simulation and test platform

Figure 5. 2 shows the actual effect and scene of a collision avoidance test with one of TSs in a strong wind and wave environment.

Figure 5. 2 Site of simulation tests

5.2 Simulation in complex environment

5.2.1 Test in multi-ship environment

In the previous research, the author has solved the problem of autonomous CA decision-making and action with a number of autonomous ships and manned ships in complex encounter situation. It is worth noting that our decision-making algorithm does not rely on the communication between ships on their respective intentions or collision avoidance strategies, and can consider the different manoeuvrability of various ship types (container ships, bulk carriers, passenger ships, high-speed ships). The encounter situation is designed as a complex situation with five OSs. The initial encounter state and their respective routes are shown in Figure 5. 3.

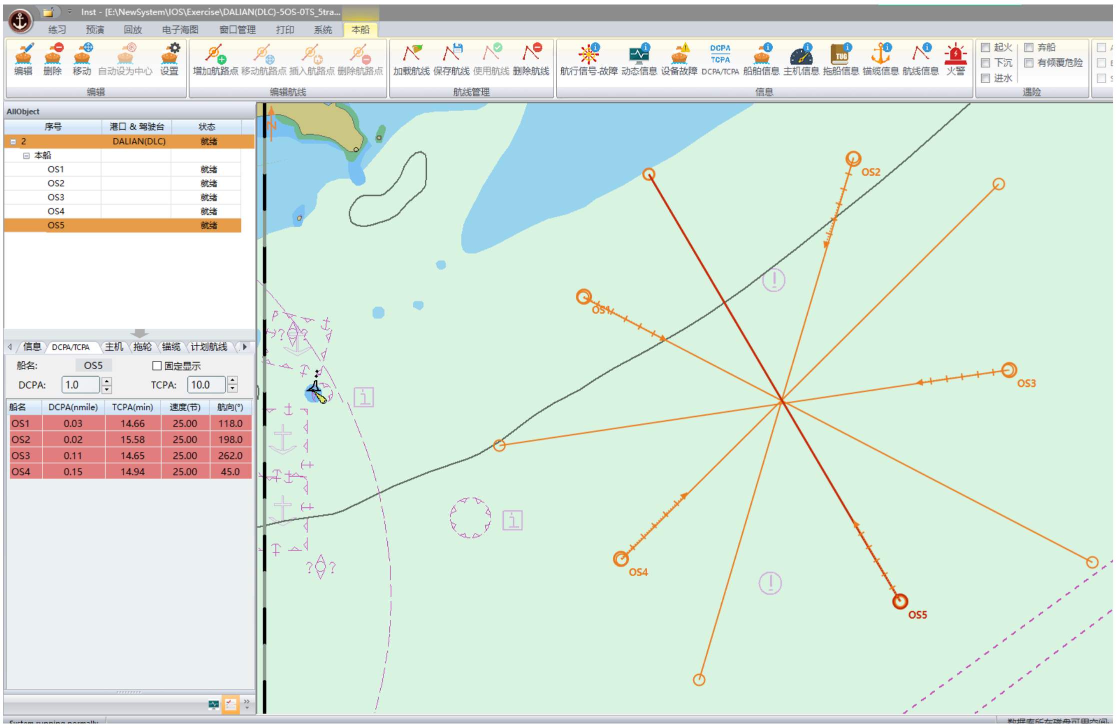


Figure 5. 3 Initial status of multi-vessel encounter situation

In the figure, OS# 1 ~ 5 each is MASS. If the safety margin is set as *DCPA* = 1 n mile, *TCPA* = 20 min, it can be seen that each ship has collision risk with at least two other ships (marked with red shadow). Taking OS5 as an example, the ship and all other ships cannot guarantee to pass at the setting safety margin on the current course and speed. The *DCPA* between OS5 and other ships is very small, ranging from 0.03 nm to 0.15 nm, and the TCPA is within 15 minutes. Therefore, it will be very difficult for each ship to coordinate in this complex situation, as the crossing and head-on situations will be mixed together.

The initial status of each MASS (taking OS1 as an example) includes speed, heading, position information, and dangerous situation with other ships, as shown in Figure 5. 4.

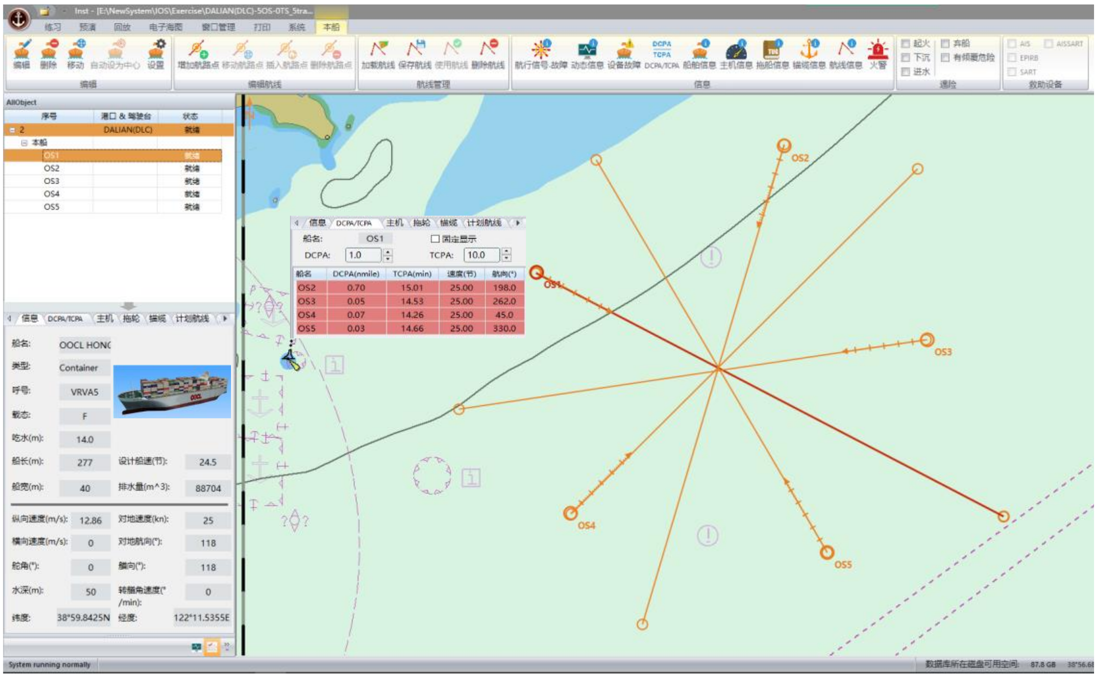


Figure 5. 4 Initial status and risk of OS #1~5

As shown in Figure 5. 5, the OS#1-5 take different steering strategies according to their maneuvering characteristics and the role in the situation. From the view of OS1, *DCPA* and *TCPA* with all other ships have reached safety values.

In Figure 5. 6, as the test went, OS#1-5 had successfully taken CA action to pass clear each other, and were approaching their respective route ends.

Through the experimental simulation of dynamic real-time mixed autonomous and non-autonomous ships, the applicability of the algorithm to the COLREGs and different ships can be seen here. Moreover this algorithm can consider the natural conditions such as external wind and flow, and can make the OS reach their goals accurately. At last, the algorithm can be integrated to the ECDIS and ship handling simulator.

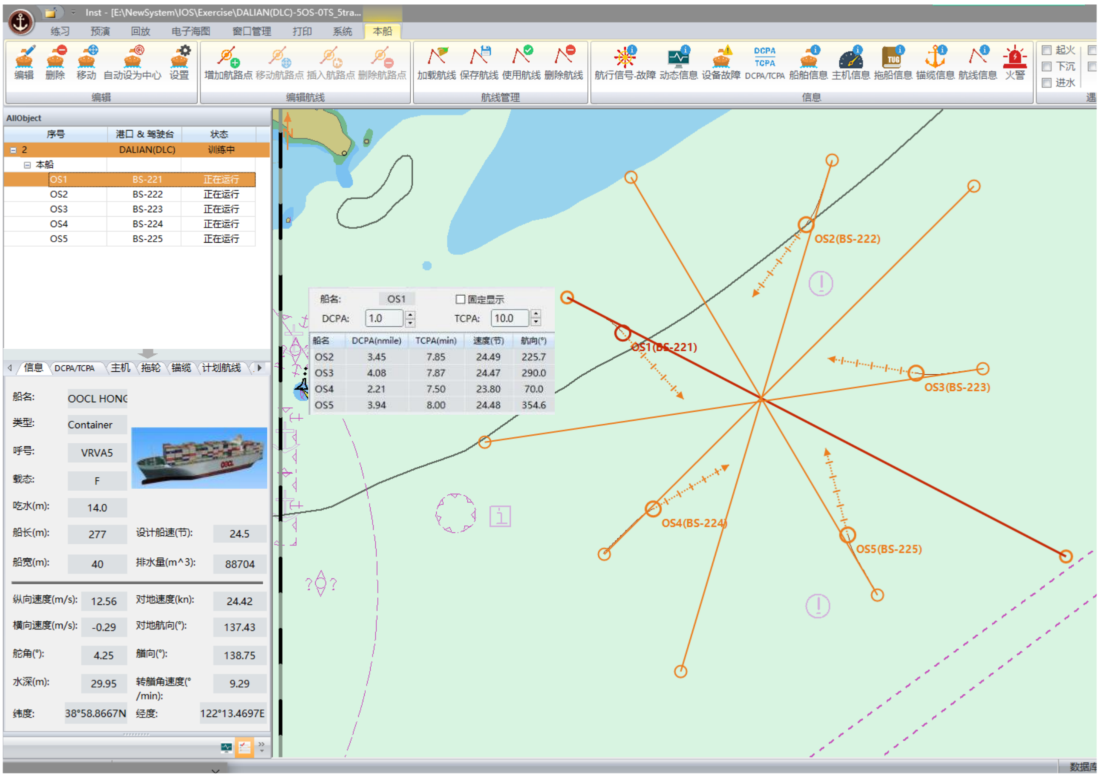


Figure 5. 5 All ship’s situation after taking CA action (in OS1’s view)

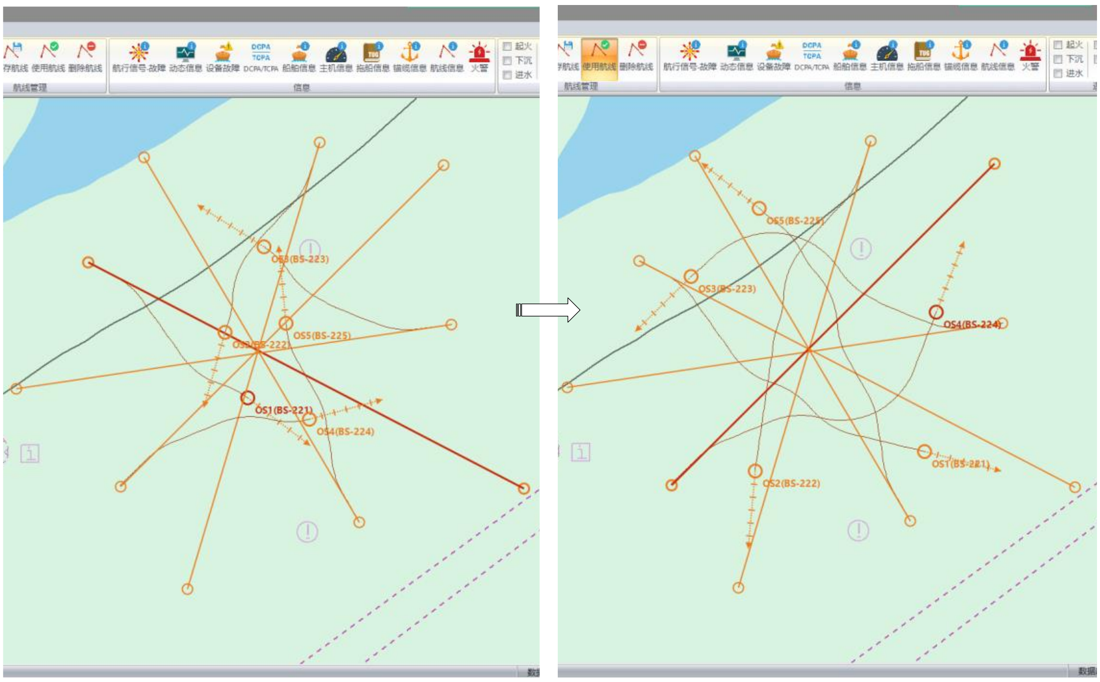


Figure 5. 6 All ship’s situation without collision risk (the view of OS4 and OS1)

5.2.2 Test in static obstacle environment

First, the safe depth contour according to the draft of OS in the chart environment should be known, so as to get the vector data of points of the contour in the electronic chart platform. Then the potential field of the environment can be generated. As shown in Figure 5. 7, the OS1's planned route crosses the island and safety contour.

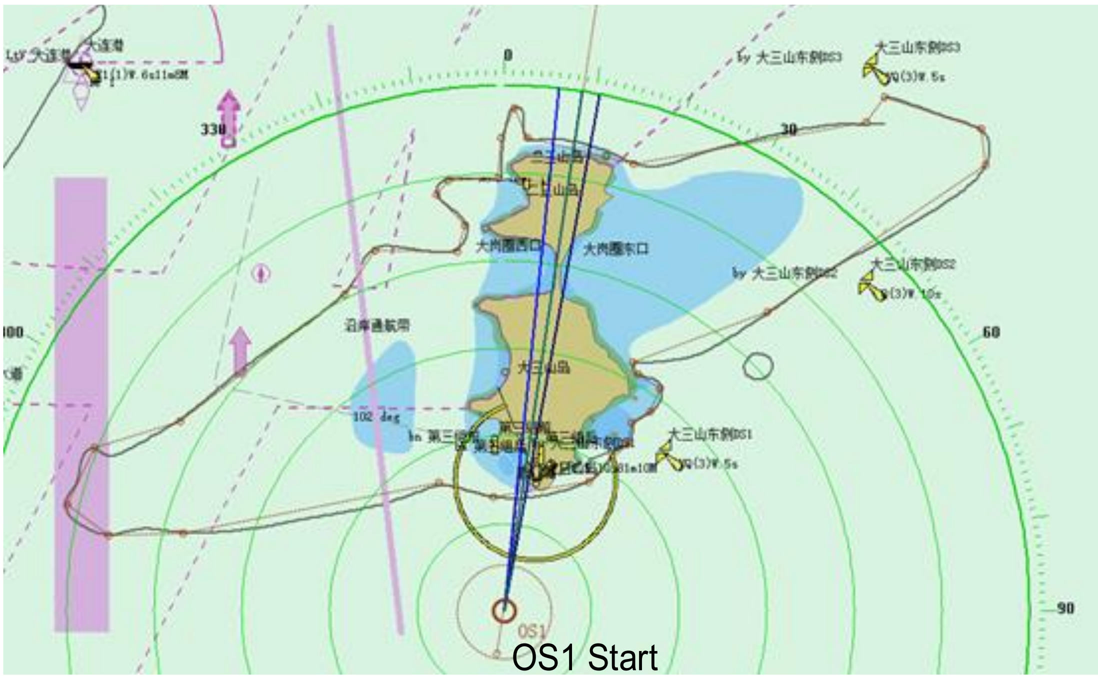


Figure 5. 7 The OS1's planned route crosses the island and safety contour

Therefore, after extracting the safety contour, the potential field of the environment is generated as shown in Figure 5. 8, and the collision avoidance path according to the algorithm in Section 4.1 is shown in Figure 5. 9.

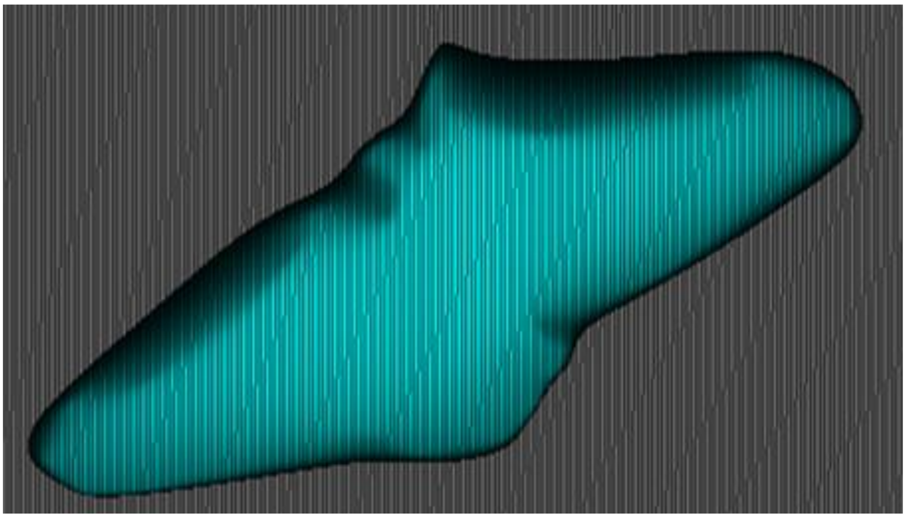


Figure 5. 8 Generated potential field of the safety depth contour

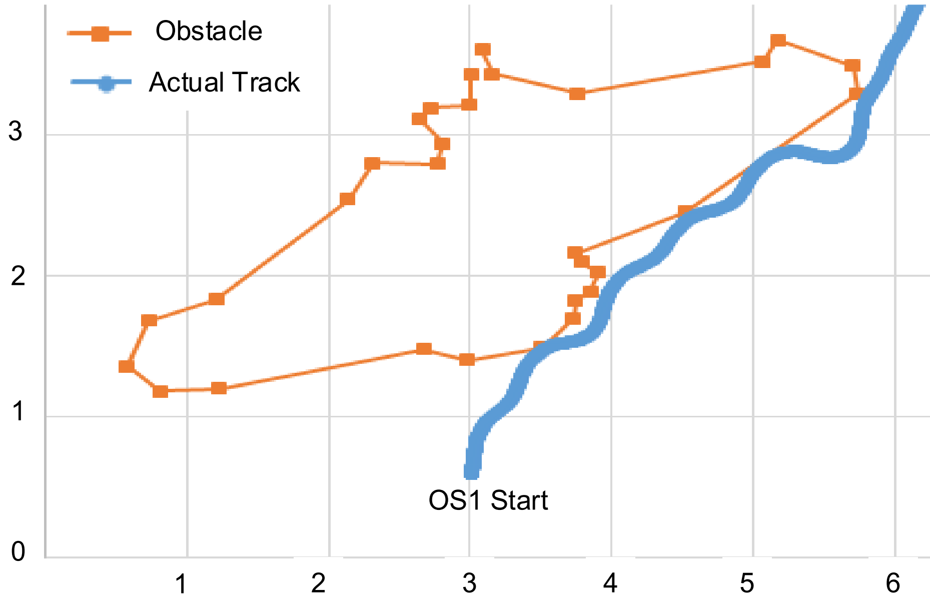


Figure 5. 9 Collision avoidance path according to the algorithm

5.2.2 Test in complex environment allowing for wind and current

The algorithm can also be applied to the complex environment with both dynamic ships and static obstacles, and can meet the requirements of COLREGs. In the simulator environment, the influence of wind and current can also be considered.

A complex water area with several rocks and shoals is selected in the test, as shown in

Figure 5. 10 Environment modeling by potential field. The critical value of safety potential field λ= 001 is chosen, when the potential field parameter β is 13.9, the influence range of potential field of a point is a circle with radius of 0.5 n mile centered on the point. Similarly, when the potential field range of the 30 m contour setting by the λ is 0.2 n mile, the potential field parameter is γ= 35, but the influence range of the potential field is not drawn in the electronic chart. After modeling in this way, the navigable water area between Obs1 and Island A is only about 0.4 n mile, while the navigable water area between Obs2 and Island A will be non-navigable.

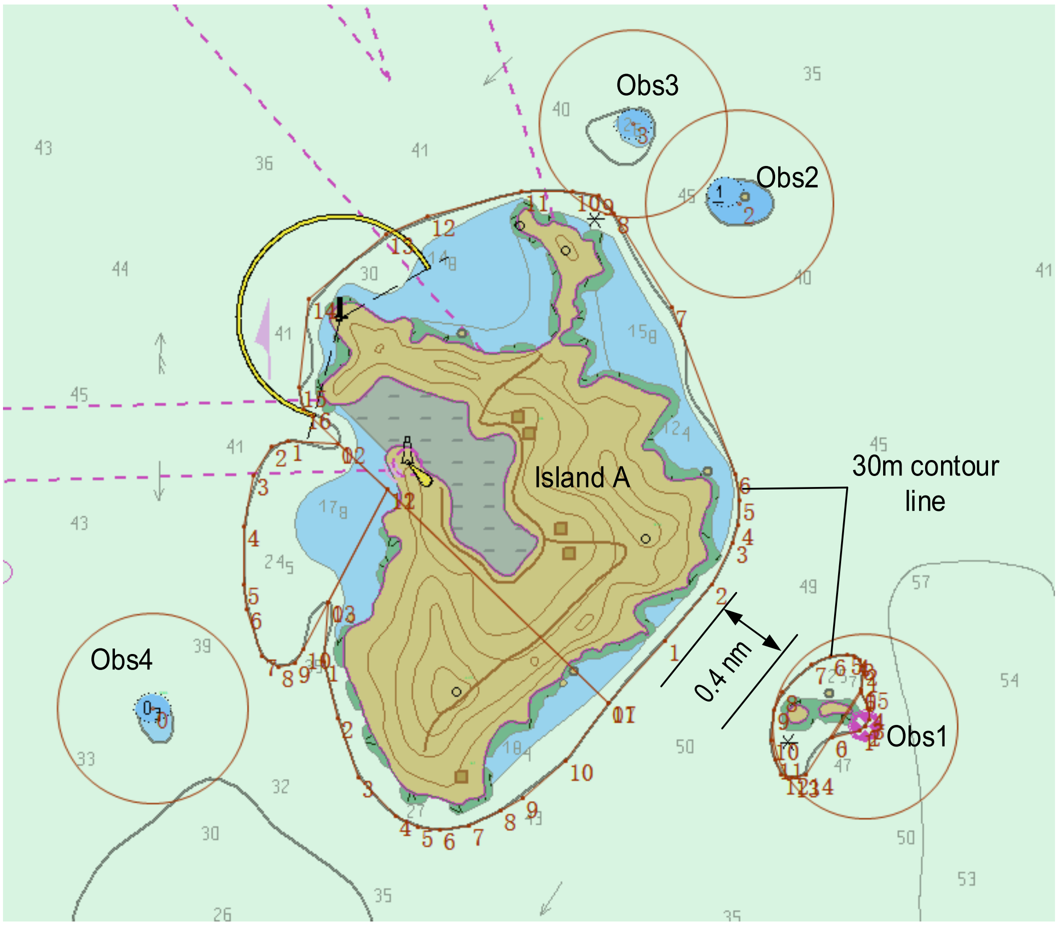


Figure 5. 10 Environment modeling by potential field

Source: 吕红光. (2019). *基于电子海图的多船避碰决策及路径规划研究*. 大连海事大学

On the basis of setting the navigation environment, one MASS OS1 and three TS#1-3 are navigating in the test water area, as shown in Figure 5. 11.

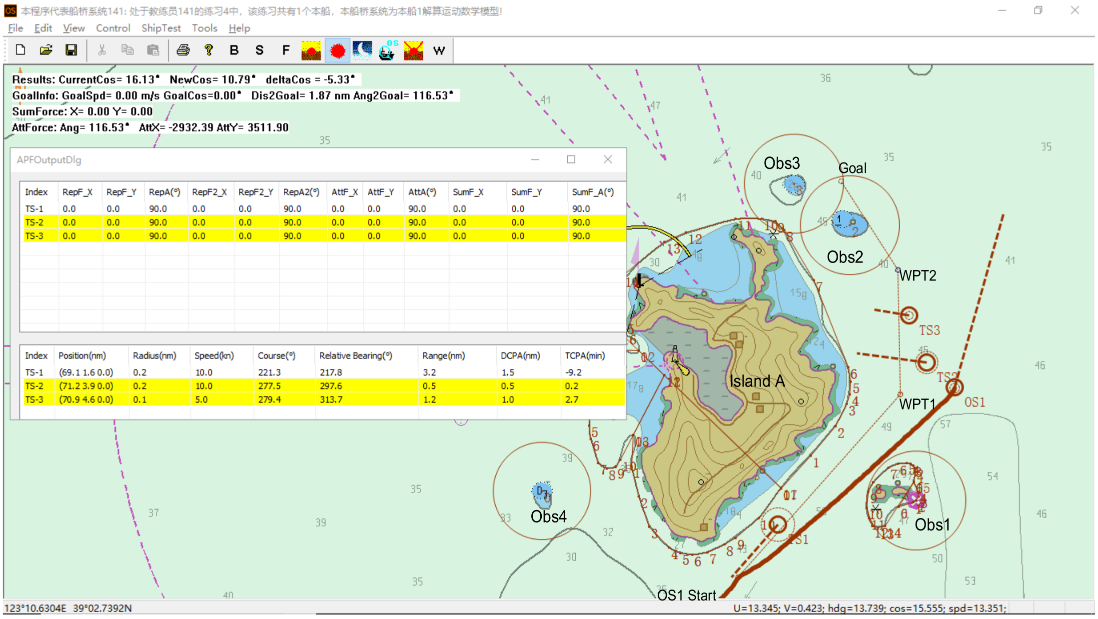


Figure 5. 11 OS1 takes CA action to avoid TS#1-3

There are two waypoints (WPT1&2) in the middle of the planned route of OS, this route is illustrated by the thin dotted line, and the actual track of OS1 is represented by a thick brown line. When sailing along the planned route, the OS1 will encounter a head-on situation with the TS1, and a crossing encounter situation with TS2 and TS3. And, in the process of avoiding, the OS1 will be affected by the nearby island A, obstacles and shoal Obs#1-4. Finally, our algorithm can make the OS1 successfully approach the goal and give way to TS1 with a suitable right turn without colliding with the Obs1 on the right. In addition, when encountering TS2 and TS3, the OS1 also give way the both ships at one time, passing through the stern and finally reaching the goal, as shown in Figure 5. 12.

In addition, the disturbance of wind and current is added to the test to verify the robustness of the algorithm when applied in complex waters, as shown in Figure 5. 13. The test adopts the following natural conditions: east wind Beaufort scale 7, and the current set is 200°, rate of current is 3 kn.

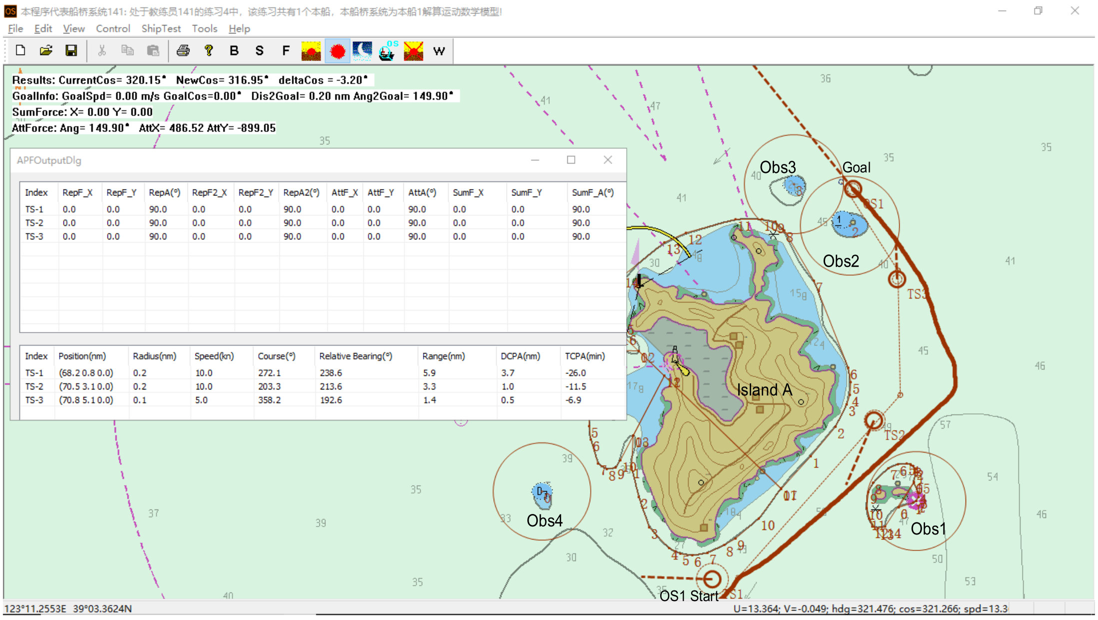


Figure 5. 12 OS1 reaches the goal without any collision with TSs and obstacles

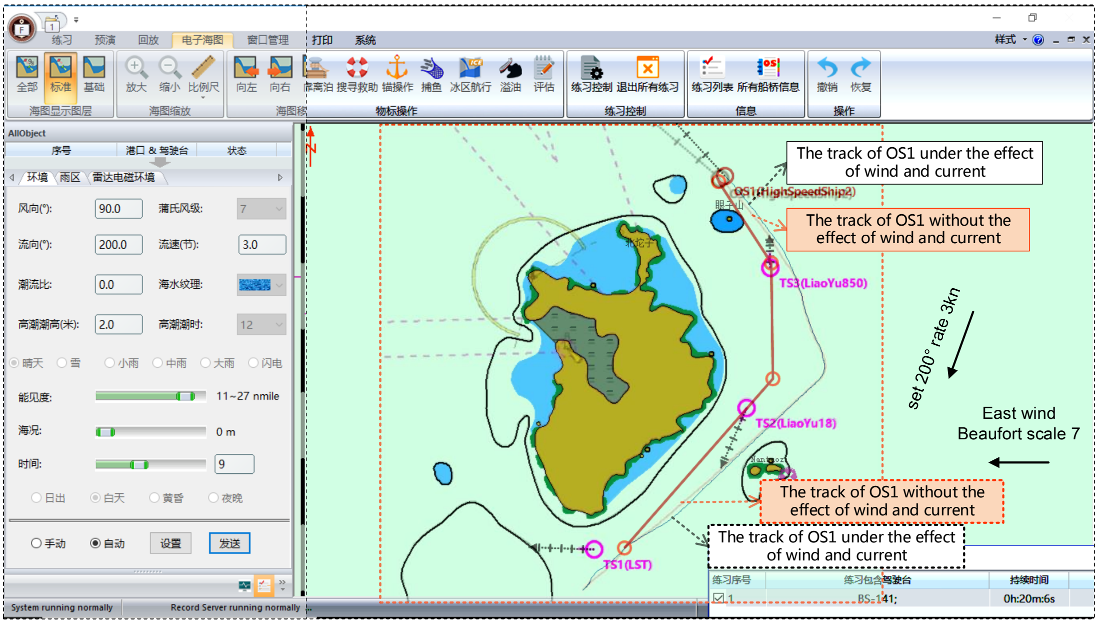


Figure 5. 13 CA track comparison for the condition with or without wind and current

Under the above weather conditions, OS1 can still avoid both static obstacles and dynamic TS#1~3, with small trajectory differences. Figure 5. 13 shows that the OS1 has a slightly larger right-turn angle while avoiding the TS1, under wind and current. In the process of avoiding TS3 to the goal, she can also keep a sufficient safe distance from obstacles such as Obs2. It can be seen that the algorithm is also adaptive and effective under large wind and current.

5.3 Fast pre-calculation of multi-ship CA decision-making

This experiment mainly verifies the feasibility of multi-ship CA assistant decision in complex environment, which provides decision reference for officers of the watch (OOWs) or remote operators on shore basis, rather than directly apply decision to the. In the experiment, a separate client program is designed, which runs in Windows environment by green installation, as shown in Figure 5. 14.

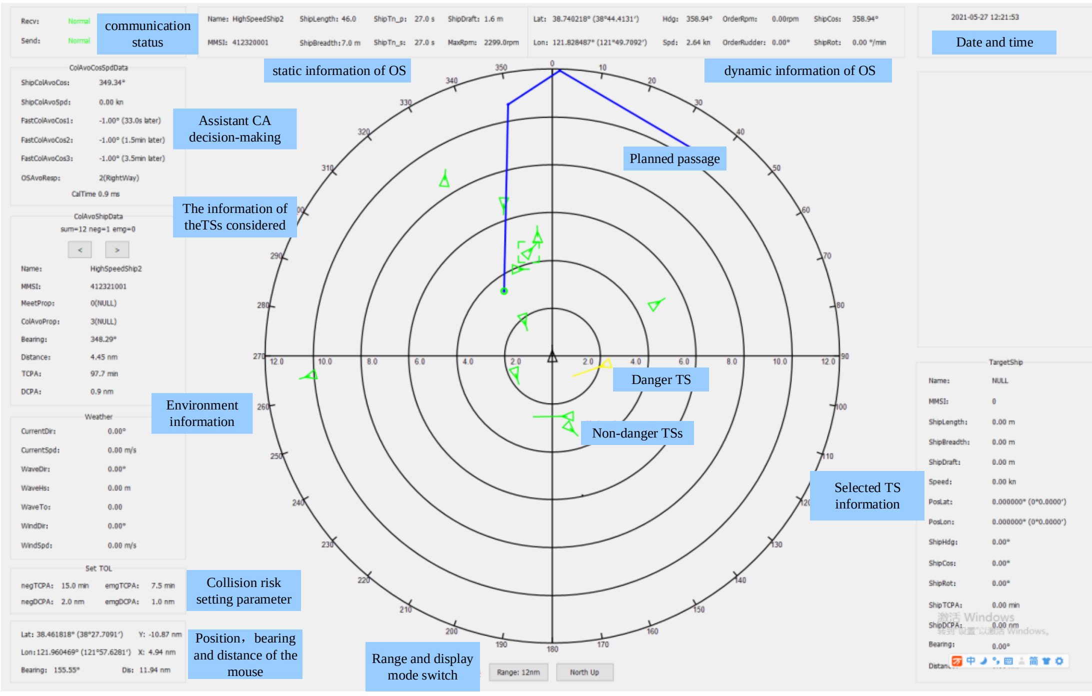


Figure 5. 14 Overview of the software for fast pre-calculation of multi-ship CA decision-making

The program opens the relevant data interface, which can be used to receive the real ship data, such as AIS and radar of other ships, which is used as input of the perceptual environment information, a base of collision avoidance auxiliary decision. Because the AIS information broadcast has some delay, and some ships are not allowed to obtain AIS data, or some ships' AIS are in a closed state, so radar signal is used as supplement and correction. But radar echo does not have the basic parameter information such as the LOA of other ships, so the information of obstacles obtained by radar is divided into two categories: one is dynamic object, with a standard ship instead；the other is static object, which is replaced by the constructed environmental potential field and is consistent with the existing methods of processing navigation obstruction information in the chart.

In the initial state, the OS1 is selected as the MASS, which is encountering a complex crossing and head-on encounter situation with the other five TSs, as shown in Figure 5. 15, in order to test the change of CA decision of the ship OS1, which can provide the operating advice to the OOWs.

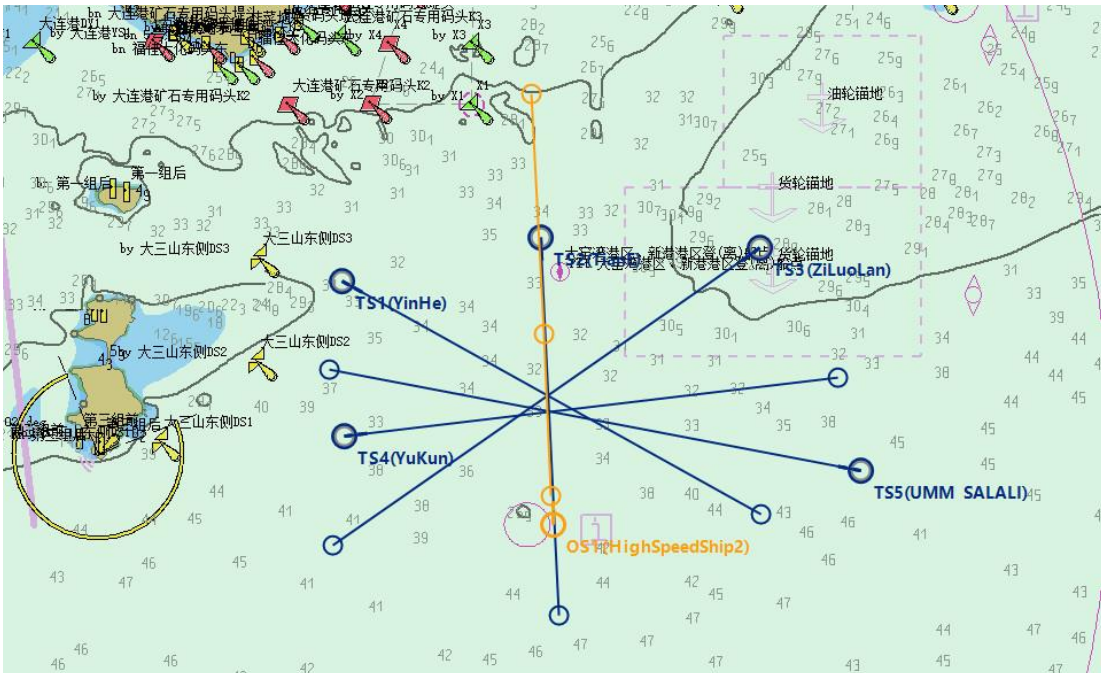


Figure 5. 15 Initial status of multi-vessel encounter situation

In Figure 5. 16, the red TS encounters a head-on situation with the OS1. It is suggested that the OOW should follow the light blue track in the figure to avoid collision with a large right turn. At the same time, the OS1 should prevent collision risk with TS3 in front of the right (in yellow color), so the OS1 should continue to turn right at a large angle and then resume original route until without collision risk.

Figure 5. 16 Initial CA decision-making suggestion

After that, if the OOW does not take action to avoid collision or miss the best time to avoid collision, the software can also continuously provide feasible CA path according to the dynamics of other ships. As can be seen from Figure 5. 17, the recommended decision-making is a larger right turn than the previous, because the turning time is delayed.

Finally, when all the dangers are eliminated, all TSs in Figure 5. 18 turn green, and the recommended path of this OS is also directly converted to the goal point.

From the above dynamic changes of recommendation decision, the practicability of the method proposed in this dissertation can be seen, which can provide real-time decision support for the duty officer.

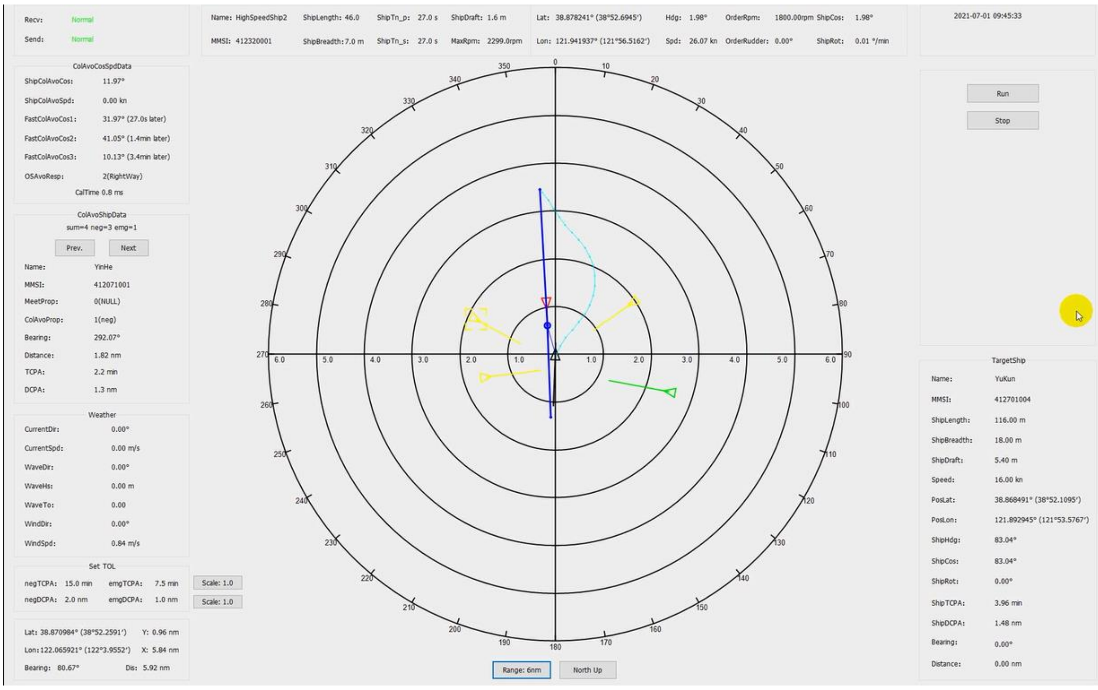


Figure 5. 17 Dynamic CA decision-making suggestion

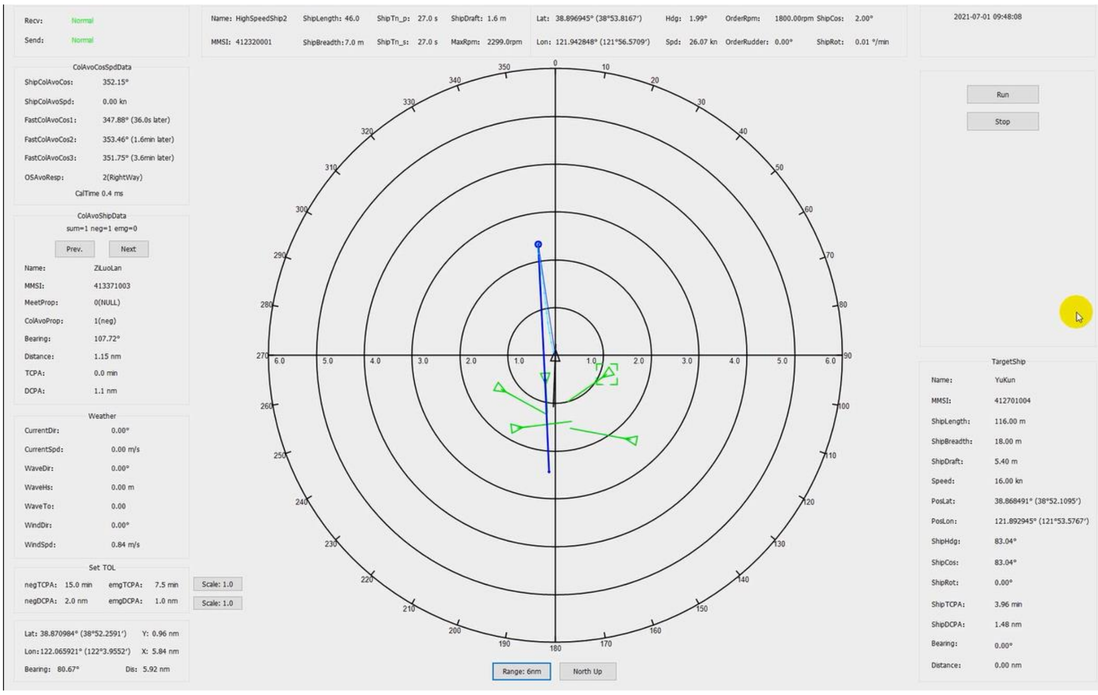


Figure 5. 18 Decision-making suggestion is to the goal when without risk of collision

5.4 Discussion

The content of this chapter is the design, test and verification of path planning algorithm in complex environment on the "full mission ship handling simulator test platform". In this platform, more accurate and real environmental information is obtained, such as electronic chart information including static obstacles and non-navigable waters, and dynamic ship data obtained from radar, AIS, etc. By doing this the test environment is upgraded.

In addition, the collision avoidance between autonomous and non-autonomous ships in complex waters with static obstacles is realized, and the influence of wind and current can be considered. In order to meet the needs of MASS to control on board or remote controlling centre, multi-ship CA assistant decision-making experiment also has been tested.

To sum up, the algorithm has achieved good results in the complex environment, but the construction of large-scale environmental potential field is limited to the calculation conditions, so it cannot be carried out at present.

6 SUMMARY AND CONCLUSIONS

6.1 Conclusion

This paper first analyzes and summarizes a large number of recent classic literature on ship automatic collision avoidance and path planning, systematically classifies and summarizes them from the perspective of methodology, and finds out the existing problems and research directions in this field. It is found that the existing problem is that it is difficult to solve the problem of automatic collision avoidance in complex waters with multiple ships and static obstacles. Therefore, based on the existing research foundation, the whole process is analyzed and designed in the aspects of environment modeling, collision risk judgment, collision avoidance or path planning decision-making and simulator verification in complex environment.

Second, the paper establishes the potential fields of points, lines and surface obstacles using electronic chart vector data, paying special attention to the modeling of concave polygonal obstacles, and proposes several complex environment modeling methods that are probably future and currently feasible for the development of MASS.

Third, combining with the judgment of safe distance and collision risk between ships, the paper designed a real-time and deterministic automatic collision avoidance method and automatic collision avoidance algorithm based on improved artificial potential field.

Forth, it is worth noting that at the present stage, there are still some difficulties in the actual operation of ships directly using the automatic collision avoidance decision. If it can provide the OOW with direct decision-making advice and feasible collision avoidance path, this also very conducive to the safe navigation of the ship. Therefore, in this paper, a fast pre calculation method is proposed to provide collision avoidance decision-making suggestions. This method can display the collision avoidance path and steering decision-making suggestions on the screen in real time by using the installed green software in the electronic chart platform, which can be used as a reference for the duty officer or remote controller.

Finally, the paper designs and completes the application test and verification of the algorithm in the "full mission ship handling simulator test platform". The verification results show that the design method has achieved good results and has a certain application prospect.

6.2 Future Work

This paper have refined and improved our team's previous work, such as proposing the methods of fast pre-calculation CA decision-making and complex navigation environment modeling, but there are still some aspects to be improved.

The proposed method is designed to suit for the complex waters, however, it also needs the combination of altering course and/or changing speed actions in collision avoidance strategy. At present, the algorithm only considers the usual course alteration CA strategy at sea. In fact, the CA methods of ships at sea include course alteration alone, changing speed or even stopping alone, or changing the course and speed at the same time. Especially in narrow waters, the diversity and flexibility of CA methods are required to be higher. Therefore, in the future research, it is proposed to explore CA strategies that are more suitable for specific waters and navigation practice.

In addition, although the dissertation can construct the potential field of a concave polygon, which is suitable for the construction of complex navigation environment, the data in electronic chart is extremely complex, and there is still a lot of detailed work to do. For example, there are a large number of concave polygons with different attributes, unclosed graphics and the situation of covering each other in electronic chart, which need to be processed automatically. In order to improve the efficiency of vector data modeling of electronic chart, the automatic screening, validity judgment and implicit function representation of concave obstacle of electronic chart data will be the next research direction.

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