

Ship Domain Model for Multi-ship Collision Avoidance Decision-making with COLREGs Based on Artificial Potential Field

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ABSTRACT: A multi-ship collision avoidance decision-making and path planning formulation is studied in a distributed way. This paper proposes a complete set of solutions for multi-ship collision avoidance in intelligent navigation, by using a top-to-bottom organization to structure the system. The system is designed with two layers: the collision avoidance decision-making and the path planning. Under the general requirements of the International Regulations for Preventing Collisions at Sea (COLREGs), the performance of distributed path planning decision-making for anti-collision is analyzed for both give-way and stand-on ships situations, including the emergency actions taken by the stand-on ship in case of the give-way ship's fault of collision avoidance measures. The Artificial Potential Field method (APF) is used for the path planning in details. The developed APF method combined with the model of ship domain takes the target ships' speed and course into account, so that it can judge the moving characteristics of obstacles more accurately. Simulation results indicate that the system proposed can work effectively.

1 INTRODUCTION

1.1 Intelligent Navigation System

The Intelligent Navigation Systems is regarded as the next generation of main auxiliary driving means. With the benefits of the improvement of computer technology, navigation technology, and sensors, also including intelligent arithmetic and methods, these systems come into practice. The accuracy of the position, velocity, acceleration and heading components of the ship is an important part of the navigation system to predict ship's location and heading, as well as an important element of improving the safety of navigation. It should be noted that the progress of modern technology has been widely used in a variety of land (Uriasz 2009, Jian, Wenjun et al. 2014), waterway (Zhonglian, Xiumin et al. 2015) and air (Ruishan, Lei et al. 2016) transport

systems to meet the complicated navigation needs in recent years. Waterway transport is still in the progress of these technologies and a considerable number of navigation functions (ie navigation prediction, propulsion control and engine control (Dongzhi, Xinping et al. 2014)) are still operated by human operators. These lacking navigation features can also compromise their respective operations with safe in narrow and crowded waters and complex ship handling at different environment conditions. Although in the above complex navigation environment, the crew can still ensure the safety of navigation, but the difficulty is still increased with the heighten of the intensity of the ship. The auxiliary driving systems, also other AGN Systems are able to solve this problem effectively, so as to reduce the burden of ship operators and reduce the risk of accidents caused by human error.

1.2 Collision avoidance and The COLREGs

The mathematical model for detecting the risk of collisions between ships in the particular ocean area is divided into two main categories: distance closest point approach (CPA) and predicted area of danger (PAD) approach. The CPA approach evaluates the risk of collision between the ship and the surrounding ship by calculating the minimum collision distance of the two vessels under the current route (Zhang, Zhang et al. 2015). However, since the difference in vessel size, heading and speed is not considered, in some cases the risk of collision is estimated to differ from the actual situation (Stahlberg, Goerlandt et al. 2012). Therefore, this method is often used in conjunction with the concept of the ship domain. The PAD approach evaluates the risk of collision by modeling the predicted track of own ship as an inverted cone and other target ships' predicted track as an inverted cylinder. The overlapping area of these two possible trajectories is the area where there is a risk of collision, and the limited size, heading and velocity variations between the vessels can be incorporated into this method. These two methods are both considered the ship speed and course conditions of continuous change, however the instantaneous variations of navigation information for example which caused by the parameter changes are not considered. In addition, in order to simplified calculation and so on, these methods are simplified by assuming the simple and ideal navigational conditions such as vessel movement under a straight line of deterministic state and parameter behavior. Obviously, the complex and volatile actual sailing situation is quite different from the ideal state.

On the other hand, in the current algorithms, most of the rules and regulations on the ocean navigation collision situation have been ignored. In practice, the phenomenon of neglect of IMO regulations has also occurred sometimes, which has become an important reason for maritime traffic accidents. Statheros (Statheros 2008) noted that about 56% of the ship's collision accidents were due to the fact that the crew did not follow the rules and regulations. Among these rules and regulations, the most important one about anti-collision are the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) (IMO (1972)). The COLREGs rules and regulations are important documents for IMO to constrain the behavior of ships sailing on the sea. It is divided into 5 parts (General, Steering and Sailing, Lights and Shapes, Sound and Light signals and Exemptions) and four Annexes containing technical requirements. Perera (Perera, Carvalho et al. 2011) discussed the details of anti-collision of two ships meeting in a particular area under the COLREGs. Furthermore, he presented a method of fuzzy logic reasoning, which can be used to assist crew to make the ship collision avoidance decision. Even though the COLREGs rules and regulations give priority to all the sailing ships' obedience to prevent collision accident, they do not provide certain operating instructions, especially for the scenario of multi-ship encountering.

COLREGs rules and regulations divide the ships meet in a water area into two kinds: the stand-on ship and the give-way ship. The stand-on ship is the ship which should get through this area as soon as

possible by keeping its speed and course. Meanwhile, the give-way ship should change its speed and course in order to clear this area for the convenience of stand-on ship's pass way. There are 3 kinds of the ship meeting scenarios, which are the head-on, take over and crossing. COLREGs rules and regulations have been discussed in the recent literatures, for example Perera (Perera, Carvalho et al. 2011) showed ever kind of the anti-collision situations, and Jinfen Zhang (Zhang, Zhang et al. 2015) discussed the multi-ship encounter collision avoidance situations.

Ship's automatic path planning, which plays an important role in autonomous voyage, is the base of most AGN functions like auxiliary driving, intelligent navigation, unmanned surface vehicle and so on. However, most ship's automatic path planning researches draw on some research methods in the field of robots especially self-driving vehicles (Lingling and Lei 2014). Due to the working environment and the relevant traffic laws and regulations are completely different, ship's automatic path planning must have something special and unique. It's a requirement of COLREGs to be further studied to cope with new problems like auxiliary driving or assist making decisions in automatic way.

1.3 Ship Domain and Artificial Potential Field

In the study of ship collision problems, it is an important issue to ensure that the shortest distance of the collision does not occur or the nearest distance that two ships can pass each other safely, which area is named ship domain since it was first proposed in the 1970s. As the first question to make sure for everyone's study of anti-collision, how to determine the shape and size of ship domain attracts researchers' attention. It is obviously that different definitions and proposals of ship domain have different shapes and sizes. At beginning of the research, people tend to focus mainly on the size and shape under standard conditions. People The standard conditions always mean a large ocean area and limited speed. The shape of ship domain is set to a certain shape and the size of ship domain is considered to be almost constant in a voyage. In further research, People attempt at using a region of the ship's historical data (like the AIS data (Hansen, Jensen et al. 2013)) in a specific sea area to extract the specific information of ship domain. Since ship domain is a kind of image description of ship collision risk, it is reasonable to be changed with different ship speed and other navigation data. Pietrzykowski (Pietrzykowski and Uriasz 2009) defined a variable ship domain with different levels of safe growth and crew's consciousness. For example, the ship domain is smaller where the navigator is familiar with the waters, since it's safer than other scenarios.

The potential field method or the Artificial Potential Field method (APF) is a classical method for robot path planning, and the unmanned surface vehicles are regarded as the kind of robot working in river, lake or sea. A typical application of artificial potential field tracing algorithm is shown in Figure 1-4. The APF method uses virtual gravitational and repulsive field force to express the relationship between the tracing robot and the obstacle and the

target. In general, the relationship between the tracing robot and the target is a mutual attraction, and the value of the virtual attractive field declines with the distance, where the potential energy is U_{at} (Fig.1). The situation between the tracing robot and the obstacle is the opposite, the value of the virtual repulsive field energy increases with the distance, where the potential energy is U_{re} (Fig.1). Then the total potential energy in every point of the area is the sum of the above:

$$\bar{U} = \bar{U}_{at} + \bar{U}_{re} \quad (1)$$

Through analogical basic mechanics knowledge, the virtual force field can be derived to the virtual attractive force and virtual repulsive force as follows:

$$\bar{F} = \bar{F}_{at} + \bar{F}_{re} \quad (2)$$

Where the virtual attractive force is $\bar{F}_{at} = -grad(\bar{U}_{at})$, and the virtual repulsive force is $\bar{F}_{re} = -grad(\bar{U}_{re})$.

By following the total virtual force at any given position, the path can be found. The route planned by this method in the area is a set of minimum virtual force field values, and that's one way to look at it. (Fig.2 and Fig.3). As its mathematical expression is elegance and simplicity, the APF method is particularly appealing. When the APF method is used in a dynamic environment like moving obstacles, the tracing robot have to keep running path planning algorithm to avoid all the obstacles and then the path planning algorithm develops into route finding.

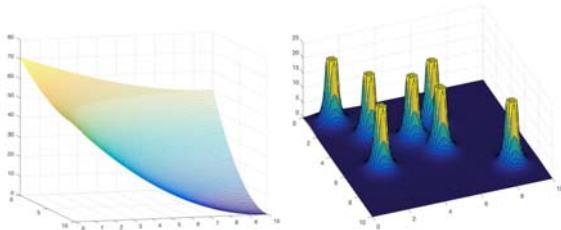


Figure 1. The gravity field of the target (x=10, y=10) and the repulsive field of 7 obstacles

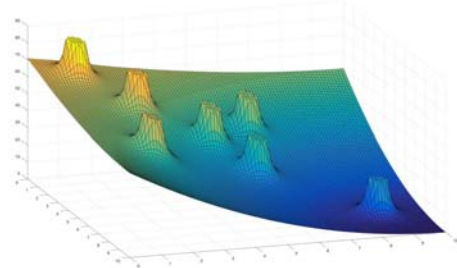


Figure 2. The final APF combined the gravity field with the repulsive field

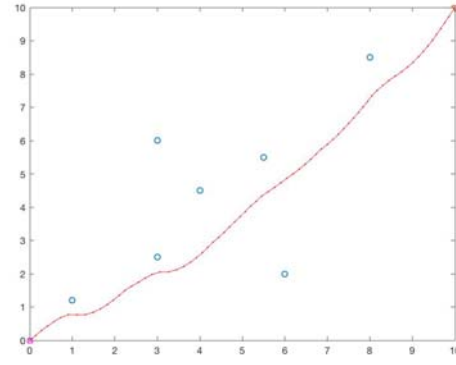


Figure 3. The final path planned from Starting Point (x=0,y=0) to the Target Point(x=10, y=10)

The intelligent surface vehicle path planning in calm water is similar to the tracing robot, but the flow field in the environment is also a factor to be considered. Rui Song et al (Liu, Liu et al. 2015, Rui, Liu et al. 2015, Rui, Liu et al. 2016) developed a multi-layered fast marching (MFM) method for unmanned surface vehicle path plan in a dynamic environment. In this method, they get the flow field in the environment, the velocity field of the target ships and the virtual force field of the fixed obstacles together. The path that planned use APF method is a continuous curve of a definite numerical composition. However, there is a great difference between the actual use requirements when it come to the situation like autonomous navigation and auxiliary driving, as the driver cannot steer the ship as accurate as the robot. To solve this problem, Lee(Lee, Kwon et al. 2004) combined fuzzy logic with APF method and developed a new autonomous navigation algorithm.

2 COLLISION AVOIDANCE UNDER COLREGS

2.1 The COLREGs rules and regulations

The COLREGs rules and regulations include 5 parts and 38 rules. Among these rules and regulations, this paper mainly focus the Part B Steering and Sailing rules. According to the COLREGs, the collision situation among two ships can be divided into head-on, crossing and over take to the route angle. And the own ship should needs to give way to all the ships that appear on its starboard side, and it is not a stand on ship until all ships are on the port side. All the collision situations are briefly described in Fig.4. In Fig.4, own ship's position is supposed to be at the coordinate origin and its course is set to Y-axis forward. Then we can define the collision situation when the target ship appears in different regions from A to F. When the target ship appears in region A, B and F, it means that the target ship is on the starboard side, own ship should give its way. Otherwise own ship is a stand on ship.

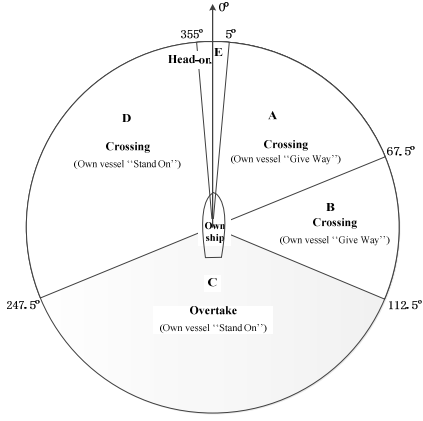


Figure 4. Brief description of the collision situations

2.2 The prepare of Path Planning

The following algorithm in 2.3-2.5 mainly references Jinfen Zhang's (Zhang, Zhang et al. 2015) research about the distributed anti-collision decision support formulation. As the system in this paper regard the COLREGs as the top layer and prepare of the path planning, it simplifies the output of the Jinfen's algorithm.

2.3 Closest Point of Approach(CPA)

CPA is the most simple and effective means to predict the target ships' position and to estimate collision risk. In this paper, CPA is calculated every time to make sure that the path planning decision is safe and the ships have large enough area to move no matter whether ships change their speeds and courses. That means that during the ships take anti-collision actions, the CPA should keep larger than set minimal value. For instance, ship1 and ship2 take actions to avoid collision, which is shown in Fig.6. Suppose with the same time start to change course, the ship 1 spend more time to change course than ship 2 (which means $T_{S1} > T_{S2}$). In the whole process of completing the collision avoidance of the two ships, there are 3 period and each period has its own CPA. which is list below, the situation is shown in Fig.5:

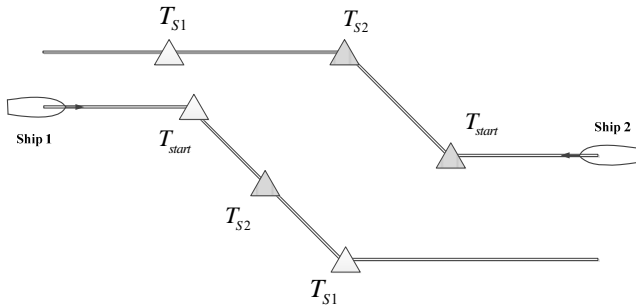


Figure 5. CPA computation for two ships

- 1 d_1 (from T_{start} to T_{S2}): from start to the end of ship2 course changing, during this period both of two ships are on the changing course;
- 2 d_2 (from T_{S2} to T_{S1}): from the end of ship2 course changing to the end of ship1 course changing, during this period ship1 is still on the changing course, while ship2 is on the original course;

- 3 d_3 (from T_{S1} the end): from the end of ship1 course changing to a time large enough, during this period both of two ships are on the original course. The CPA of this two ships' anti-collision action is the minimum of the three. And the value of CPA can be calculated as below:

Suppose the two moving ships' initial position are $P_{S1} = (x_1, y_1)$ and $P_{S2} = (x_2, y_2)$, whose speed are v_{S1} and v_{S2} , and course angles are θ_{S1} and θ_{S2} . After t time the position for ship i is:

$$P_{Si}(t) = (x_i(t), y_i(t)) = (x_i + v_{Si}t \sin \theta_{Si}, y_i + v_{Si}t \cos \theta_{Si}) \quad (3)$$

During the period $(0, T)$, the distance of two ships at time t is

$$D(t) = |P_1(t)P_2(t)| = \sqrt{(x_1(t) - x_2(t))^2 + (y_1(t) - y_2(t))^2} = \sqrt{At^2 + Bt + C} \quad (4)$$

where

$$\begin{aligned} A &= (v_1 \sin \theta_1 - v_2 \sin \theta_2)^2 + (v_1 \cos \theta_1 - v_2 \cos \theta_2)^2 \\ B &= 2[(x_1 - x_2)(v_1 \sin \theta_1 - v_2 \sin \theta_2)^2 + (y_1 - y_2)(v_1 \cos \theta_1 - v_2 \cos \theta_2)^2] \\ C &= (x_1 - x_2)^2 + (y_1 - y_2)^2 \end{aligned}$$

The minimum of $D(t)$ is a typical Extreme Value Problem of Quadratic Function.

It should be noted that CPA is the basis of path planning and the main means of decision-making verification.

2.4 Collision Avoidance for Give-Way Ships

This part of the algorithm is designed for making sure that whether own ship is stand-on ship or give-way ship, and then calculates the course change range and the speed change range of the give-way ship and the stand-on ship if necessary. According to the COLREGs and the main requirements of the system, the two main points of the algorithm just mentioned are as follows.

- 1 Judgment of give-way ship and stand-on ship
As shown in Fig.6, the own ship should give way to all the target ships apparent on own ship's board side, otherwise if there is no ship on the board side of the own ship, the own ship is the stand on ship.
- 2 The speed change range of the give-way ship
Due to the underactivity of the ship's dynamic system, although the collision avoidance operation is rarely performed by changing the speed, it is still effective in some specific cases. Especially when the cruise of the two ships is very small, which is discussed by perera and Jinfen. Speed changing is only accorded when the course angle is smaller than θ , which is a given value. Speed declines 10% of the original speed each time and update the CPA by using the method discussed in 3.2.1. Since the speed change often matches the track change, the set speed is reduced by 50% of the original speed. The above two steps are shown in Fig.6.

- 3 The course change range of the give-way ship
 This part of the algorithm is the main part, and focus on the change range of the course angle and the course time. The course change time and angle change from the minimum to the maximum. Each step of the change update the value of CPA until the CPA is larger than the given value. This part of the algorithm is shown in Fig.7.

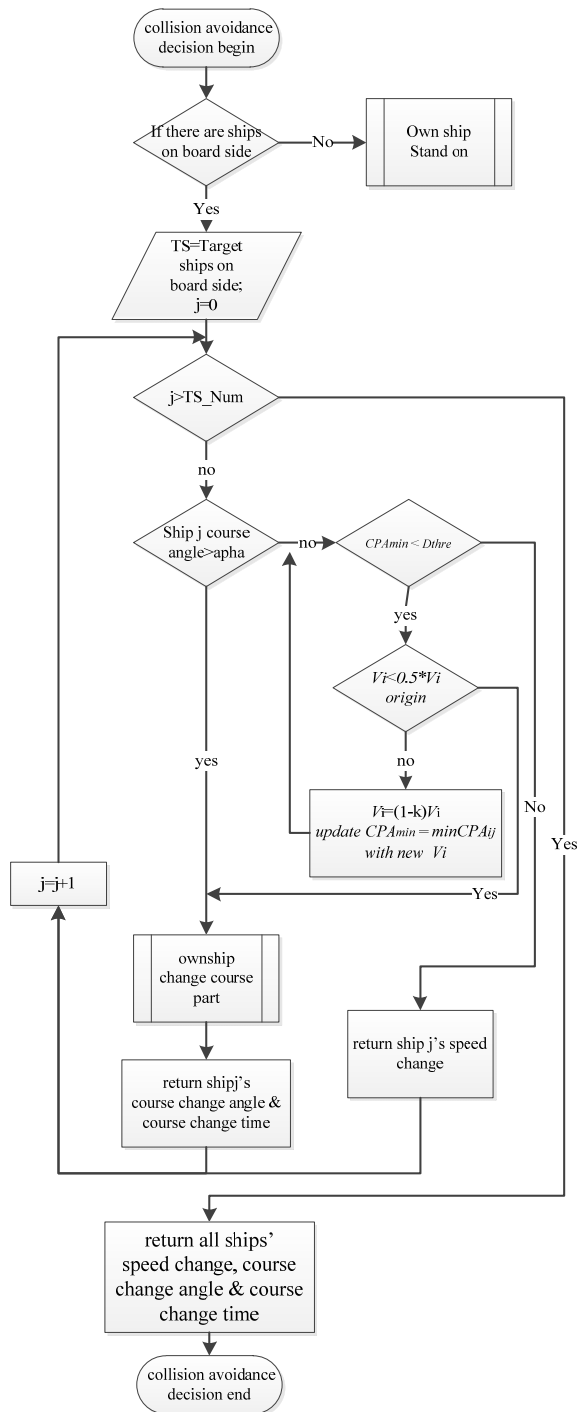


Figure 6. The procedure of own ship give-way decision

2.5 Collision Avoidance for Stand-On Ships

According to the COLREGs, the stand on ship should keep its speed and course to pass the meeting situation, at the bases of safety. However, the problem is much complex in the real world, sometimes the stand on ship cannot tackle the problem without change course as well as the speed. For instance, the

target ship may not be able to give its way in time. By study the situation that the stand on ship has to take measures, it is obviously that the measures that stand on ship take is on the opposite of the give way ship. It means that the stand on ship should turn left and accelerate compared with the give way ship's turning right and slow down. Since the COLREGs requirement that in the process of avoiding collision the give ways ship has to take the measures as much as possible from the stand boat's stern through the formation of the port side of the port side of the situation. In order to avoid a conflict with the action of give way ship, the action of the stand on ship should be facilitated by the bow from the give way ship. So it is the reasonable for the stand on ship to apply the above collision avoidance strategy. Based on the above analysis, the anti-collision decision for stand on ship can be made in the same way of the give way ship. The only different is turn left and accelerate.

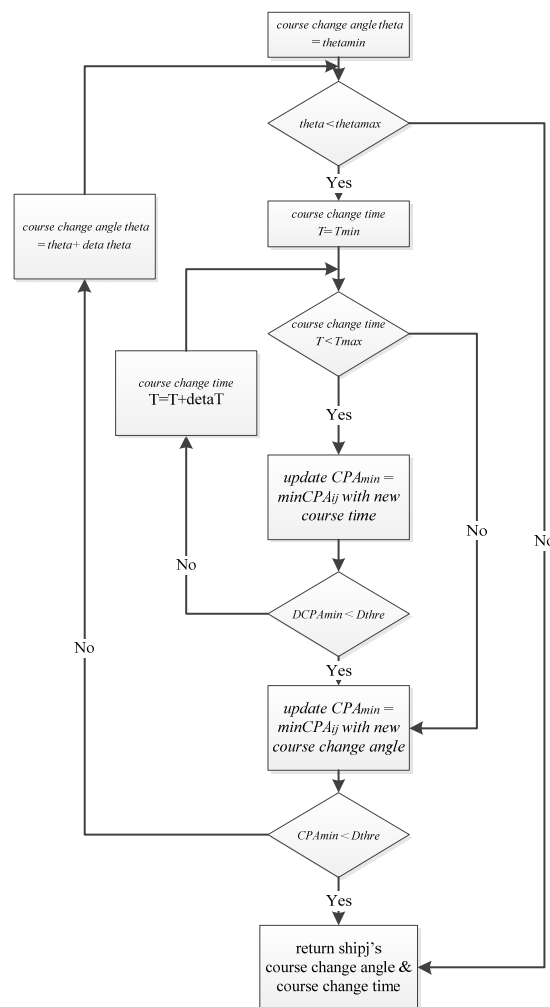


Figure 7. The own ship change course part is shown

3 PATH PLANING USING APF METHOD

3.1 the Model of the Potential Field

APF method will be used in this part, in order to contribute the path planning in details. The purpose of building the target ships' potential field is to describe the impact of the target ships. Through the

establishment of the target ship potential field, the own ship and the target ship can keep a safe distance by altering the course and the speed. For the target ship, the risk of the vicinity of the target ship in the vertical and horizontal distribution along the target ship is not uniform, taking the characteristics of the ship and the actual situation of navigation. For example, the main factor affecting the safety of a ship in the horizontal direction is the distance between the ships and the speed is also an important factor in addition to the distance. Therefore, the modelling of the target ship potential field will also be combined with the vertical and horizontal characteristics of different models of design. In this paper, the main innovation of the target ship potential field is the model used the ship's longitudinal influence as the skeleton, to extend the way to achieve the impact of the ship distribution of the description.

The longitudinal potential of the target ship is calculated as follows. The local coordinate system is established based on the direction of the target ship body direction and the intersection of the ship's horizontal axis and the vertical axis. The entire longitudinal potential field distribution is a piecewise function, the calculation formula as follows:

$$A_{ship} = \begin{cases} U_{ship} & p \in \beta \\ \frac{v_r}{K - S} & (p \in \alpha) \cap (v_r > 0) \\ 0 & (v_r \leq 0) \end{cases} \quad (5)$$

where,

U_{ship} is the ship potential constant, which represents the maximum value of the ship's potential field

v_r is the relative speed of the own ship and the target ship, when the speed of the two in the same direction, the speed of the own ship is greater than the target ship $v_r > 0$, on the contrary $v_r < 0$.

K is the longitudinal distance between the own ship and the target vessel.

S is a set safe distance, where $S = v_r \cdot \Delta T + s_{mn}$, ΔT is the system delay, which is related to sensor delay and calculation delay, s_{mn} is a set of extended safety distances.

When the point p is in the area β (which is shown in Fig.9.), The longitudinal potential field is distributed as a constant U_{ship} . Considering the relative velocity v_r which is the target ship and the own ship, when $v_r \leq 0$, the relative distance between the target ship and the ship is gradually increased, and the longitudinal potential value is 0. When $v_r > 0$, it indicates that the distance between the ship and the target ship is gradually reduced. The more dangerous the potential value is, the more the relative velocity is, the more dangerous and the potential value is positively correlated with the relative velocity. The above-mentioned longitudinal potential distribution reflects the risk distribution of the target vessel in its longitudinal direction, the influence of the ship on its surrounding environment in its transverse direction, and its overall potential field is formed on the basis of longitudinal, which is shown in Fig.10, Fig.11, Fig.12.

The calculation of the target ship's potential is obtained by multiplying the longitudinal potential field A_{ship} by the transverse potential field. The horizontal calculation rule is a kind of Gaussian function. The whole calculation method is shown in the formula (6)

$$e_{mn} = A_{ship} \exp\left(-\frac{D^2}{2\sigma_v^2}\right) \quad (6)$$

where,

D is the potential distance of moving ship in different area which is shown in Fig9

σ_v is the convergence coefficient of the ship's potential, and determines the horizontal influence range of the potential field.

σ_v

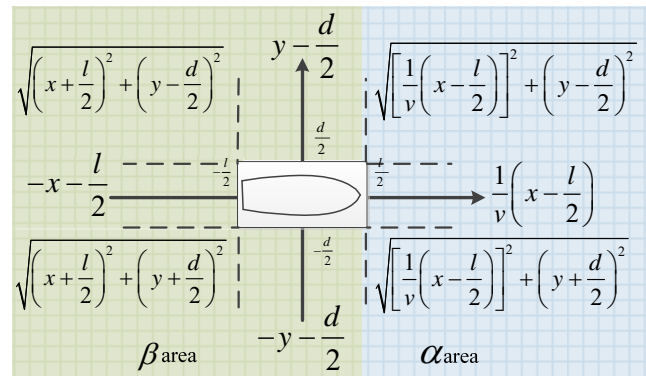


Figure 8. The potential distance of moving ship

3.2 case study of the Potential Field

1 As discussed above, the potential field of a ship which position is (0,0), course angle is 0, speed is 10, and the Outline Dimension is 20×5 is shown in fig from origin, x-y, x-z and y-z four angles, the shape of the potential field of one ship is shown in Fig 10.

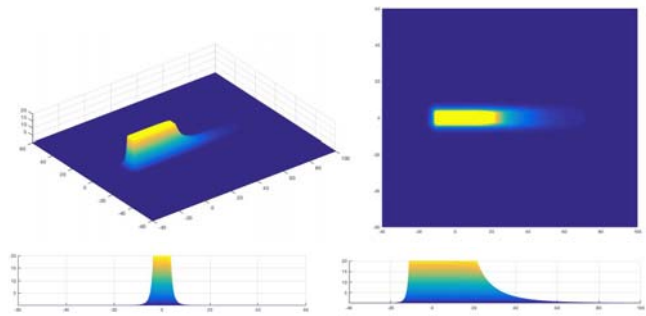


Figure 9. Four visual angles of the potential field of one ship

2 The potential field of two crossing ships from origin, x-y, x-z and y-z four angles is shown in fig11 which position, course angle, speed and the shape is shown in table1. The superposition of the virtual force field when the ship is approaching can be clearly seen in the figure.

Table 1. The details of two ships

Ship	Position	Course Angle	Speed	Outline Dimension
Ship 1	(0, 0)	0	10	20×5
Ship 2	(40, -40)	90	10	20×5

3 The potential field of four crossing different ships from origin and x-y visual angles is shown in fig12 which position, course angle, speed and the shape is shown in table2. The superposition of the virtual force field when the ship is approaching can be clearly seen in the figure.

Table 2. The details of four different ships

Ship	Position	Course Angle	Speed	Outline Dimension
Ship 1	(100,100)	210	5	30×10
Ship 2	(100, -100)	135	10	20×6
Ship 3	(-50, 70)	-60	10	10×3
Ship 4	(-150, -100)	60	10	30×5

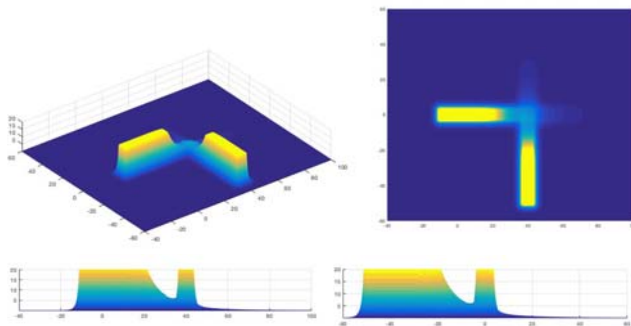


Figure 10. Four visual angles of the potential field of two crossing ships

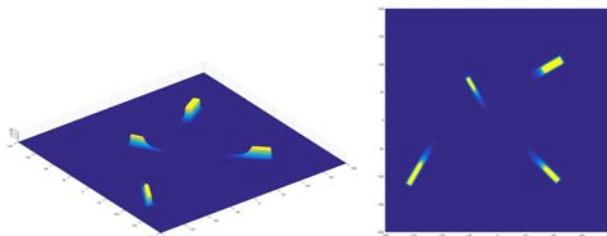


Figure 11. The origin and x-y visual angle of the potential field of four crossing ships

4 THE DISTRIBUTED MULTI-SHIP COLLISION AVOIDANCE

This paper proposes a complete set of solutions for multi-ship collision avoidance in intelligent navigation, by using a top-to-bottom organization to structure the system. The system is designed with two layers: the decision-making layer for path planning and the control layer for path following. Fig.13 show the system's organization and elements.

The up layer is the decision-making layer, which is designed to prepare for path planning. First step of the decision-making layer is the collision avoidance function under COLREGs. This part of the algorithm is designed for making sure that whether own ship is

stand-on ship or give-way ship, should keep the speed and course or change them. The second part of the up layer's function is path planning in details by using the APF method.

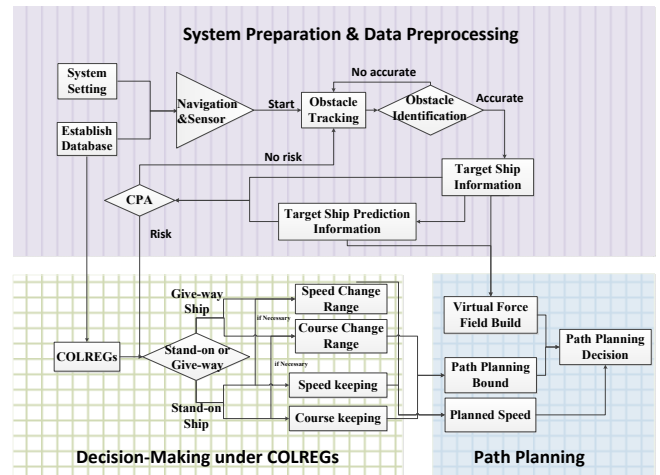


Figure 12. The system's organization and elements

5 CONCLUSIONS

A multi-ship collision avoidance decision-making and path planning formulation is studied in a distributed way. This paper proposes a complete set of solutions for multi-ship collision avoidance in intelligent navigation, by using a top-to-bottom organization to structure the system. The system is designed with two layers: the collision avoidance decision-making and the path planning. Under the general requirements of the International Regulations for Preventing Collisions at Sea (COLREGs), the performance of distributed path planning decision-making for anti-collision is analyzed for both give-way and stand-on ships situations, including the emergency actions taken by the stand-on ship in case of the give-way ship's fault of collision avoidance measures. The Artificial Potential Field method(APF) is used for the path planning in details. The developed APF method combined with the model of ship domain takes the target ships' speed and course into account, so that it can judge the moving characteristics of obstacles more accurately. Simulation results indicate that the system proposed can work effectiveness.

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