Intelligent Automation And Soft Computing, 2019
Copyright © 2019, TSI® Press
Vol. 25, no. 4, 789–804
https://doi.org/10.31209/2019.100000083

Deterministic Vessel Automatic Collision Avoidance Strategy Evaluation Modeling

Liu Hongdan, Liu Qi, Sun Rong

Automatics College Harbin Engineering University,

ABSTRACT
Based on the concrete sailing parameters of the own vessel and the target vessel demarcate and the division of stages of vessel collision avoidance, the deterministic vessel automatic collision avoidance strategy evaluation model is constructed by the relevant factors which influence ships encounter dangerous situation. By means of inputting the relevant parameters of the collision avoidance strategy into the feasibility evaluation model, the estimated judging curves of the pivotal parameters of vessel collision avoidance can be validated, furthermore, the deterministic collision avoidance evaluation model for single vessel can be extended to the multi-vessels collision avoidance evaluation. Finally, by means of comparing the actual cases of the vessel collision avoidance and the diagrammatic sketch of two vessels' sailing trajectory, the feasibility report of the collision avoidance strategy can be generated, and then the feasibility and effectiveness of the deterministic evaluation model could be proved.

Keywords: vessel collision avoidance strategy; collision avoidance evaluation model; Deterministic analysis; collision risk index model.

1 INTRODUCTION

IN the process of the vessel automatic collision avoidance, after determining the meeting situation between the two vessels, the collision avoidance opportunity and a collision avoidance action of the own vessel should be taken based on the analysis of the collision risk index (CRI), which lays the foundation of generating the collision avoidance scheme, (Foris, Jakub & Vladimir Kuzmin, 2015).Meanwhile, all of them above are gotten under the condition of complying with the applicable rules of the COLREG (IMO, 1972). Thus the reasonableness and effectiveness of the collision avoidance strategy have a direct impact-ion to the vessel's responsibility, thereby, "the most effective avoidance action" could be judged. However, the development of a practical vessel collision automatic avoidance evaluation system is a very complex project, due to the uncertainty of the regulations for preventing collision is the biggest reason, which shows that there have not been uniform and authoritative models for CRI, the encounter situation, the vessel domain, the stages of the collision avoidance, and then the uncertainty of the external environment in the process of collision avoidance, the indeterminacy of the specific quantity described in every stages (KarahaliosH, 2014). At present, the models of vessel collision avoidance evaluation can be divided into macro-evaluation and micro-evaluation according to the difference of the research focus (Di Zhang, Xinping Yan & Jinfen Zhan, 2016). The macroscopic collision avoidance evaluation is based on the data of historical collision accident and hydro-logical meteorology, the qualitative concept is obtained by methods of investigation and observation, and the risk of vessels collision in a large range of given waters is evaluated in all its aspect (Kaneko F, 2002).The microscopic collision avoidance evaluation mainly focuses on the collision accident under the specific situation, the collision risk of the own vessel and the target vessel in this area is quantified by setting the area for the own vessel, and establishes a collision liability analysis model by means of studying the relevant content of the vessel collision responsibility division (Zhang D, Yan X & Yang, Z, 2013). The study of micro-collision avoidance evaluation is still in the preliminary research stage as a whole. An evaluation system for single target ship collision avoidance is set

CONTACT Liu Hongdan liuhongdan131@126.com

up. The system three-level processing model based on data fusion technology is described in this paper (Liu & Hu, 2005);From the concepts of ship domain and arena, a composite evaluation of ship collision risk index is proposed by applying fuzzy theory and fuzzy comprehensive assessment based on the principles of geometry in ship collision.(XuWen, Hu Jiang-qiang & Yin Jian-chuan 2017).

Wang Delong et al who combined the expert system with the membership function assessment method, established an automatic evaluation system based on the vessel control simulator(Wang, Ren&Xiao2015) ; Jiang Cong intended to use the analytic hierarchy process to establish a comprehensive scientific evaluation system and calculate the weights of the index parameters, and then the feasibility of the method is verified through an anti-collision example(Jiang,et,al,2007, June); Zhu introduced TOPSIS to evaluate the vessel collision avoidance action, established the evaluation index system and the corresponding evaluation mathematical model (Zhu, Wu & Shi, 2010,August). Q Xu et al used the fuzzy logic multiplication method to evaluate the collision avoidance by judging the relation among vessels (Xu, et.al. 2009).

In summary, the uncertainty of the evaluation results will be increased due to the application of a large number of uncertain parameters. Therefore, the model of deterministic vessel automatic collision avoidance strategy evaluation for given-way vessel is established, the collision avoidance strategy used for assessment was gotten under the condition that own vessel is the given-way vessel and the target vessel sails straightly. Meanwhile, the evaluation model and the collision avoidance scheme comply with the applicable rules of the COLREG. The process of evaluation is following: firstly, the important influence parameters of the process of the collision avoidance including the DCPA and the TCPA are studied, which are based on the own vessel and the target vessel's motion geometry model, the size and the sign of the DCPA and TCPA of the two vessels under the conditions of different circumstances are also confirmed. Secondly, based on the collision avoidance parameters in the collision avoidance strategy and the collision avoidance scheme evaluation model, there will be some changing curves of the DCPA and TCPA in the process of the sail route, which includes before and after the collision avoidance before and after the reorientation for single vessel and multi-vessels. Through the exploration of the change rules of the DCPA and TCPA generated by various possible avoidance actions the validity of collision avoidance process is verified, which provides the theoretical basis for the sailor to establish the avoidance scheme. Finally, based on the actual vessel collision avoidance cases, the feasibility of the collision avoidance scheme and the effectiveness of the collision avoidance model are verified on account of the movement model of the collision avoidance of the target vessels. (Statheros, Howells & McDonald-Maier, 2008).

2 THE DIVISION OF THE VESSEL'S ENCOUNTERING STAGE

BASED on the division of the collision avoidance stages, the relevant factors, which influences the collision risk, are analyzed, including the distance of closest point of approach (DCPA), the time of closest point of approach (TCPA), and the collision risk index (CRI); Moreover the mathematical models of DCPA and TCPA for different collision avoidance stages are calculated to construct the risk level of the own vessel and the target vessel at different stages. By entering the relevant parameters of the collision avoidance scheme into the assessment model, the changing curves of the assessment parameters during the collision avoidance can be generated. Then the vessel collision avoidance scheme assessment model for the own vessel can be obtained.

2.1 DCPA and TCPA

DCPA is the distance of closest point of approach between two vessels. In the relative motion radar, the size of the DCPA is the vertical dimension from the center of the circle to the relative movement line of the target ship, whose unit is the sea mile (n mile), in which the CAP is the closest point of the approach that means the foot of a perpendicular (Hansen, et, al, 2013).The DCPA and TCPA models in figure1 are built on the basis of the known information such as the location information, the navigation speed and the heading. The implementation process of the DCPA and TCPA is shown in the following figure1 (LIU Dongdong, SHI Guoyou & LI Weifeng, 2018).

1) The heading cross angle of the target vessel and the own ship:

$$C_t = \varphi_t - \varphi_0 \tag{1}$$

2) The component of the own vessel’s speed in the x-axis and the y-axis direction：

$$\begin{cases} v_{x0}' = v_0 \cdot \sin(\varphi_0 + \triangle\varphi) \\ v_{y0}' = v_0 \cdot \cos(\varphi_0 + \triangle\varphi) \end{cases} \tag{2}$$

3) The component of the target vessel speed in the x-axis and the y-axis direction：

$$\begin{cases} \mathrm{v}_{xt} = v_t \cdot \sin(\varphi_t) \\ v_{yt} = v_t \cdot \cos(\varphi_t) \end{cases} \tag{3}$$

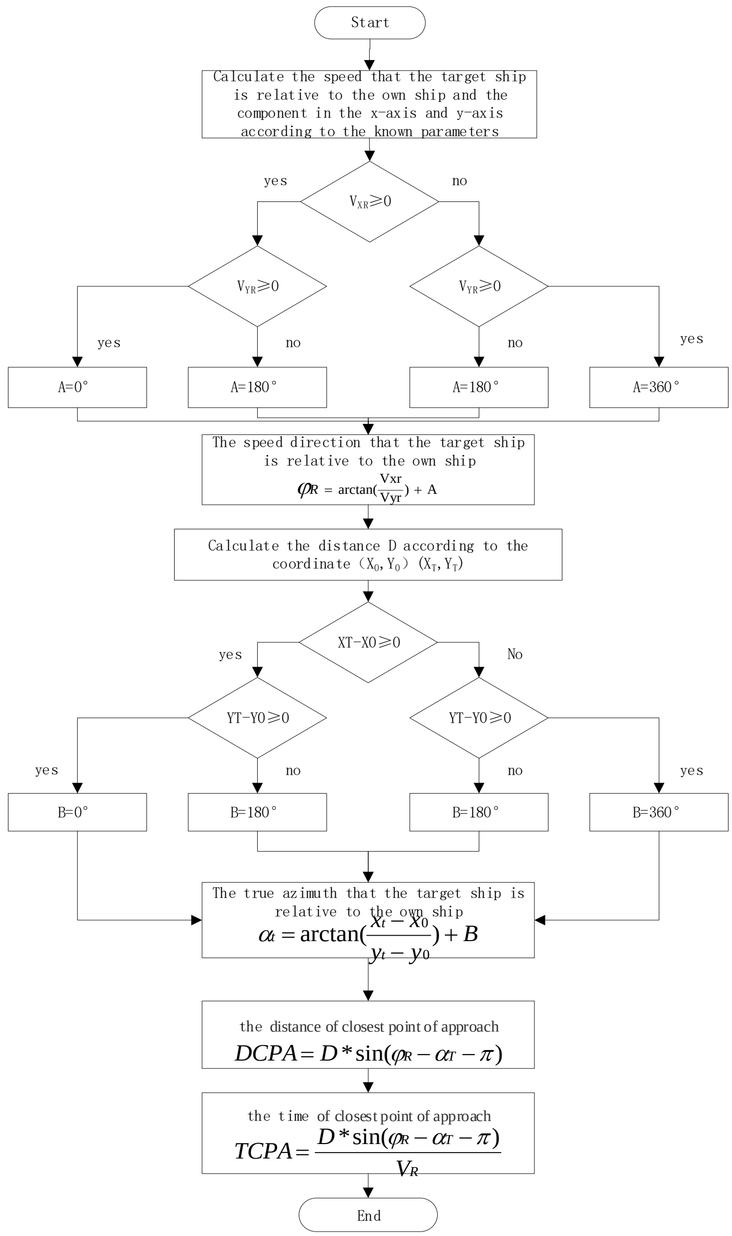


Figure 1 the realize the process of DCPA and TCPA Set own vessel at the initial position (x_0, y_0), speed V_0, heading for φ_0, collision avoidance angle $\Delta\varphi$; target ship (x_t, y_t), speed is V_t, heading for φ_t. Then:

4) The speed at which the target vessel is moving in the x-axis and the y-axis direction of the own vessel:

$$\begin{cases} v_{xr}' = v_{xt} - v_{x0}' \\ v_{yr}' = v_{yt} - v_{y0}' \end{cases} \tag{4}$$

5) The size of the relative movement speed of the target vessel:

$$v_r' = \sqrt{v'^2_{xr} + v'^2_{yr}} \tag{5}$$

6) The direction of the relative movement speed of the target vessel:

$$\varphi_r' = \arctan \frac{v_{xr}'}{v_{yr}'} + \alpha \tag{6}$$

$$\alpha = \begin{cases} 0^\circ & v_{xr} \geq 0, \ v_{yr} \geq 0 \\ 180^\circ & v_{xr} < 0, \ v_{yr} < 0 \\ 180^\circ & v_{xr} \geq 0, \ v_{yr} < 0 \\ 360^\circ & v_{xr} < 0, \ v_{yr} \geq 0 \end{cases}$$

Among them：

7) The distance between the own vessel and the target vessel:

$$D = \sqrt{(x_t - x_0)^2 + (y_t - y_0)^2} \tag{7}$$

8) The azimuth angle that the target vessel relative to the own vessel:

$$\alpha_t = \arctan \frac{x_t - x_0}{y_t - y_0} + \beta \tag{8}$$

$$\beta = \begin{cases} 0^\circ & xt - x0 \geq 0, yt - y0 \geq 0 \\ 180^\circ & xt - x0 < 0, yt - y0 < 0 \\ 180^\circ & xt - x0 \geq 0, yt - y0 < 0 \\ 360^\circ & xt - x0 < 0, yt - y0 \geq 0 \end{cases}$$

9) the distance of closest point of approach (DCPA):

$$DCPA' = D \cdot \sin(\varphi_r' - \alpha_t - \pi) \tag{9}$$

10) the time of closest point of approach(TCPA)：

$$TCPA' = D \cdot \cos(\varphi_r' - \alpha_t - \pi) / v_r' \tag{10}$$

2.2 The value distribution of the DCPA and TCPA

The DCPA plays an important role in collision risk index the distance between the two vessels in a dangerous situation. There will be collision for own vessel under the condition that the DCPA is less than the safety of the distance, and the TCPA is used to express the urgency degree of the two vessels, therefore, whether or not the existence of collision risk is determined by the TCPA when the DCPA is unchanged.

The sign of the DCPA and the determination of the risk of collision can be affected due to the own vessel and the target vessel's different encounter situation in Figure 2.

From the point of view of the target ship (T.S.), the DCPA is negative when the own vessel is on the right side of the relative trajectory, and the DCPA is positive when the vessel is on the left side of the relative trajectory. The expressions of the DCPA and TCPA are as equations (9) (10), if the DCPA is positive then $\sin(\varphi_R - \alpha_T - \pi)$ is greater than zero. As a result, there can be gotten $\varphi_R - \alpha_T - \pi \in [0, \pi] \cap [-\pi, -2\pi]$. The motion diagrams of the own vessel and target vessel are shown in Figure 3:

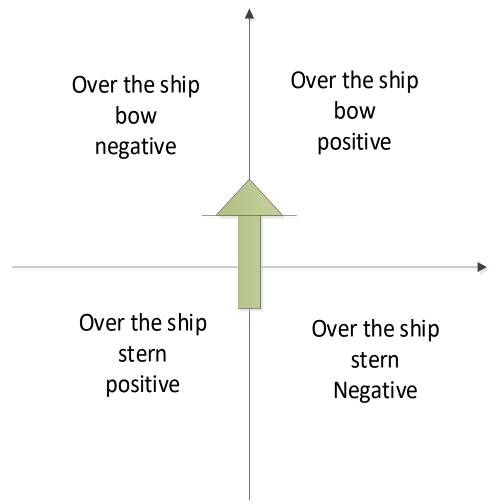
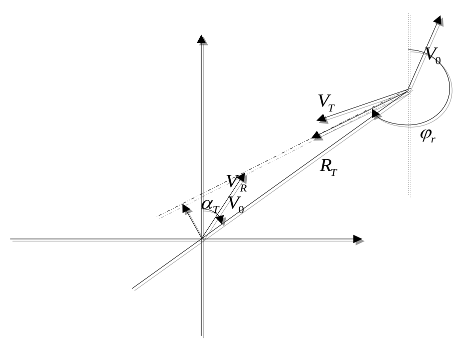
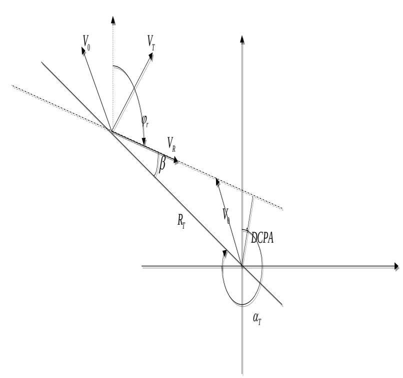


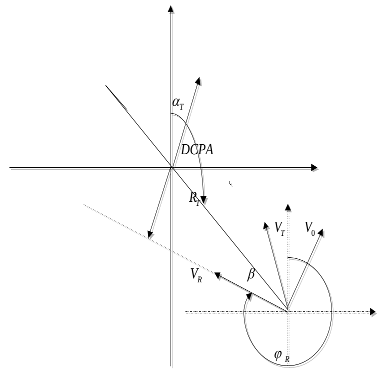
Figure 2 **DCPA value distribution**



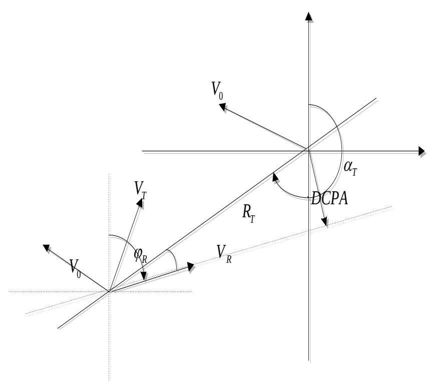
(1)T.S. is on the right side of the bow



(2) T.S. is on the left side of the bow



(3) T.S. is on the right side of the stern



(4) T.S. is on the left side of the stern

Figure 3 **Schematic diagram of motion parameters of the two vessels**

Under the condition that the relative trajectory is the direction from the target vessel to the own vessel, the DCPA is positive when the target vessel is on the right side of the own vessel's bow, meanwhile, the target vessel is on the right side of the own ship's stern, which means that the own vessel is located on the left side of the relative movement speed line; The DCPA is negative when the target vessel is on the left side of the own ship's bow, then the target vessel is on the right side of the own ship's stern, which means that the own vessel is located on the right side of the relative movement speed line; Based on the DCPA decision model under different circumstances, it is possible to confirm not only the closest distance of the two vessels but also the relative motion relation vessel (over the bow or the stern) directly according to its symbol, which can be applied to any encounter situation. Therefore, DCPA value distribution lays the foundation for the analysis of the feasibility for the vessel collision avoidance scheme.

2.3 Geometrical modeling of collision avoidance stages

The vessel collision avoidance evaluation model is achieved under five stages of collision avoidance including the direct sailing, the pre-collision avoidance stage, the post-collision avoidance stage, the pre-return stage, and the pro-return stage.

Moreover, the feasibility of the overall collision avoidance program can be verified by correctness of the collision avoidance parameters. At the end, the sailor can avoid the collision and improve the collision avoidance skills according to the assessment results.

1) Collision avoidance evaluation modeling

Before the implementation of the collision avoidance in figure 4, the initial CRI should be judged first (LAZAROWSKA, 2014). The initial state of the two vessels' azimuth can be gotten by the initial information of the two vessels. Then the DCPA and TCPA are calculated based on the above formula. Whether there is a collision between the two vessels at this time or after some time of the direct sailing can be determined. Secondly, under the premise of the current judgment of the situation without the vessel should sail straight and calculate the real-time size of the CRI. If at some point the CRI exceeds 0.6, which is the threshold value of the collision risk occurrence of vessels, therefore, it is necessary to calculate the coordinates, the distance of the two vessels after the direct sailing, the azimuth angle, the relative velocity and the direction angle of the target vessel which is relative to the own ship. Then the DCPA, the TCPA and the CRI at this time also can be calculated, laying the foundation for collision avoidance operation. The size of the CRI before the collision avoidance action and the correctness of the collision parameters obtained can be confirmed.

If the collision avoidance scheme is not correct, this collision avoidance task fails. The implementation process is shown in the figure. In this paper, when the CRI quantization model is established according to the fuzzy mathematics method (Perera, Carvalho & Soares, 2011), the sign symbol of the TCPA is taken as a condition to determine that whether the collision risk exists. By referring to the relevant literature (Liu, Wu & Jia, 2004), when the TCPA is less than 0, the own vessel has passed the closest meeting of the two vessels. The geometric movement model of the two vessels shows that the reverse extension line of the two vessels' speed intersects, to determine that at this point there is no collision possible for the two vessels. It means that the dangerous situation has been lifted when the TCPA is less than 0.

The own vessel performs the collision avoidance operation in a certain collision time. At the same time, the speed and course of the two vessels did not change compared with the stage when the own vessel begins to avoid collision. However, due to the change of the latitude and longitude of the two vessels, the distance between the two vessels and the true azimuth that the target vessel is relative to the own one will be changed, which will lead to the change of the DCPA, the TCPA and the CRI. The process is shown in Figure5. Generally, when the own vessel is sailing in a collision avoidance angle, the CRI with the target vessel is reduced compared to the moment that the own vessel turning. At this time, the correctness of the vessel's collision avoidance decision can be determined again.

2) Returning assessment modeling

Own vessel completes the collision avoidance action in the direction of the collision avoidance angle after a period of time (collision avoidance time). The own vessel starts to return when there is no collision risk between the two vessels. At this moment, the coordinates, the latitude and the longitude of vessels are the same with the ones in the last stage that the collision time ends. However, the relative speed is changed due to the changes of course.

Thus, the CRI between the two vessels can be affected, causing that the own vessel constitutes a second collision hazard to the target vessel during the period of the return. Therefore, the feasibility of the return operation of the own vessel should be assessed; the assessment process is also divided into the pre-return and the pro-return. First of all, the own ship's movement modeling CRI analysis needs to be performed, as shown in Figure 6, in the process the CRI needs to still be less than 0.6 in order to ensure that the anti-collision strategy is correct (Lazarowska A, 2014).The speed of the two vessels remains unchanged during the voyage, according to the collision avoidance parameters in the collision avoidance scheme which is to be evaluate, the latitude and longitude coordinates of the two vessels can be obtained after a period time of return. Meanwhile, the speed and course of the two vessels did not change compared with the stage when the own vessel begin to return.

But due to the change of the latitude and longitude of the two vessels, the distance between the two vessels and the true azimuth that the target vessel is relative to the own one will be changed, which will cause the change of the DCPA and the TCPA. Then the CRI will change correspondingly. Generally, when the own vessel is sailing in a return angle, the CRI with the target vessel increase compared to the moment that the own vessel is returning. However, it is still less than 0.6. As a result, at this time the correctness of the ship's return decision can be determined.

3 FEASIBILITY ASSESSMENT MODELING OF SINGLE-VESSEL COLLISION AVOIDANCE

UNDER the condition that the own vessel, as the given vessel, has the plenty of time to take the collision avoidance action a lonely. In order to evaluate the collision avoidance strategy of the own vessel, the important influence parameters include the DCPA and the TCPA during collision avoidance should be studied deeply. Based on the geometric model of the two vessels, the size and the sign symbol values of the DCPA and TCPA in different meeting conditions can be verified. Secondly, based on the collision avoidance parameters in the scheme and the collision avoidance scheme evaluation model, the collision curves of the single and multi-vessel DCPA and the TCPA of every stage of the collision can be obtained. Through the exploration of the changing rules of the DCPA and TCPA generated by the various possible avoidance measures in the vessel avoidance, the validity of collision avoidance process is verified, which provides the theoretical basis for the driver to establish the avoidance scheme. Finally, based on the actual vessel collision avoidance cases, the feasibility of the collision avoidance scheme and the effectiveness of the collision avoidance model are verified based on the movement model.

3.1 Feasibility Evaluation Modeling of Collision Avoidance scheme

Combined with the above description about the vessel at the various avoidance stages and the parameters of the initial collision avoidance scheme and for the relevant reference point in the entire collision avoidance process, the feasibility of the collision avoidance program evaluation can be given based on the collision avoidance rules' compliance in the avoidance process.

The determination of the coordination of the target vessel action such as when it comes to the poor visibility whether the two vessels at the same time take collision avoidance action is also important. The process of the evaluation modeling is shown in the following figure 7. This feasibility evaluation model of the vessel collision avoidance scheme is based on the timing of the collision avoidance that the CRI determines. And the changing curves of the DCPA, TCPA and CRI in each stage are output according to the key parameters in the collision avoidance scheme. Then the effectiveness of the avoidance action can be checked and until the two vessels no longer have the risk of collision. If there is an error in the collision avoidance stage, the wrong report as well as the wrong content will be output to facilitate the further adjustment of the program. If there is a mistake during the stage of the return, then the error report will be given about that whether the mistake can be adjusted artificially to facilitate the operator during the return.

3.2 Simulation Analysis of the Feasibility Evaluation of the Collision Avoidance

In order to verify the validity and feasibility of the collision avoidance evaluation scheme, the own vessel and the target vessel are represented by the initial heading, the speed, the longitude and the latitude, which can be gotten by Automatic Identification System (AIS) and Automatic radar plotting aids (ARPA) In different encounter situation by COLREGs (Fukuda G & Shouji R, 2017, December), the collision avoidance method adopted mostly is the steering, and taking into account specific character of safe ship control process, characterized by great course changes in range from 20° to 90°.

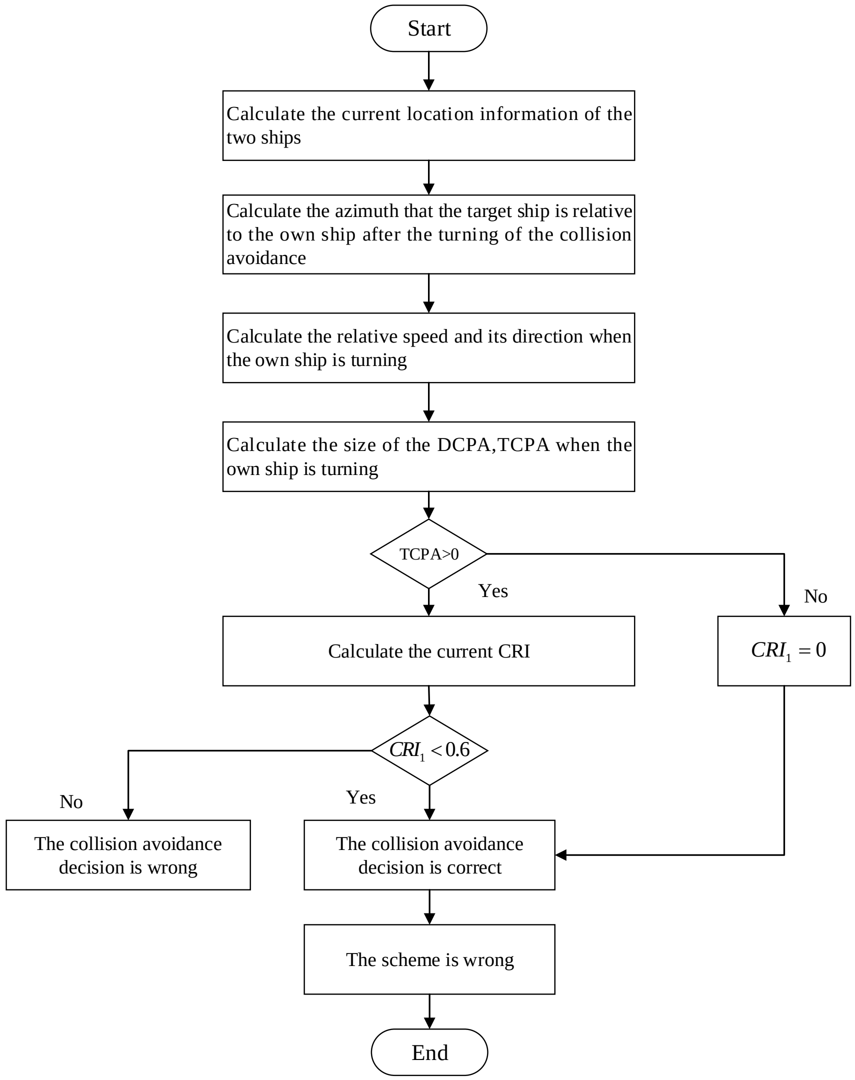


Figure 4 The CRI before collision avoidance

Furthermore, Rule 8(b) of COLREGS requires collision avoidance angle be large enough to be readily apparent to another vessel observing visually or on radar. Therefore, the change of course is better over 25° to make the target vessels to attention. And then the schematic diagram of collision avoidance process is in figure8, which shows the collision avoidance parameters including the collision avoidance angle, the return angle, the total collision avoidance time, the collision avoidance time and the return time all of these parameters can be used as the parameters for the collision avoidance evaluation model (Wang, Ren & Xiao, 2015).

The location points of the own vessel in the completion of the whole collision avoidance process in turn are the A, B, C and D. and the total time of collision avoidance t, the collision avoidance angle α and the return steering angle β ,the collision avoidance time t_a and the return time t_r can be calculated, the relation is as follows:

$$t_a \cdot \sin\alpha = t_r \cdot \sin\beta \tag{11}$$

Taking the right small intersection side of the starboard as an example, the operation process of the feasibility evaluation model for collision avoidance strategy is described in detail. The movement parameters from Automatic Identification System (AIS) for the cross encounters two vessels are as follows: the course of the own vessel is 0°, the speed is 8, the latitude and longitude is (0,0);the course of the target vessel is 250°, the speed is 12, the latitude and

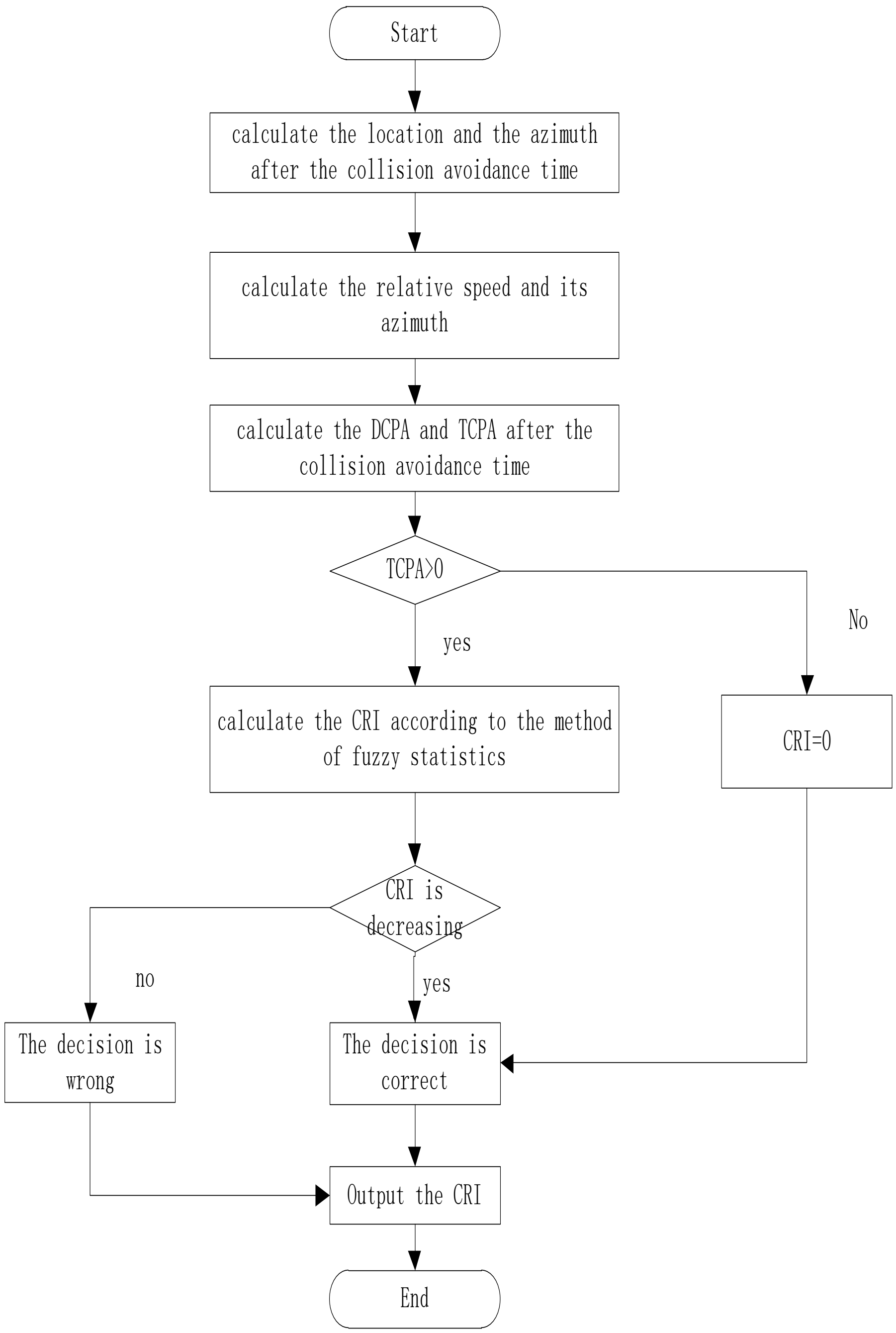


Figure 5 **The CRI after collision avoidance**

longitude (6,8); after the own vessel and the target vessels have been running for 5.2632min, the own vessel takes the action of collision avoidance ,and the total collision avoidance time is 55.0211min, the collision avoidance angle is 35.88°, and the return angle is 18.59°.The collision avoidance time and the return time are 0.3231h=19.3841 min and 0.59 h=35.6370 min respectively. Under the condition of keeping the speed constant, the coordinates of each position of the own vessel and the target vessel can be calculated. Based on the above parameters the movement process diagram that includes five stages or six moments can be obtained in figure 9.

As can be seen from the figure, on the one hand, based on the parameters given above, the collision diagram of each stage can be obtained. It is clear from the diagram that the DCPA is getting smaller significantly and the CRI increases after some time for the direct sailing. Then the own vessel turns to avoid the collision, and the DCPA has been significantly increased compared with the start of the collision avoidance stage. Furthermore, there is no risk of collision in return phase of the vessel.

And on another hand, based on the single-vessel collision avoidance evaluation model in figure 11, the changing curves of the parameters, which affect the size of the CRI during the process of the avoidance, can be output. The decision model of the vessel collision avoidance, which includes the important six moments in the whole process, can be received. The same initial parameters are inputted, the resulting curve is as shown below:

The simulation results show that the initial CRI of the two vessels is 0.48<0.6, and there is no risk to be in collision between of them. The two vessels continue to keep straight sailing, the CRI of the two vessels reaches 0.62> 0.6 after 10 minutes. At this point the own vessel turns to avoid collision, then the CRI fells to 0.20 <0.6, which shows collision avoidance decision is correct. After the collision avoidance time, the own vessel starts to return. From the figure, the CRI increased to 0.57 <0.6, the risk in this stage of collision between the two vessels is very small to determine that the return decision is correct. After the completion of the return, the own vessel sails back to the original route. At this time, the CRI of the two vessels is 0, indicating that the own vessel has passed the closest meeting of the two vessels (TCPA <0), that is, there is no risk of collision between the two vessels. The result of the collision avoidance scheme is accordance with the movement diagram at all stages. Therefore, it not only proves the feasibility of the collision avoidance strategy, but also proves the validity of the collision avoidance evaluation model.

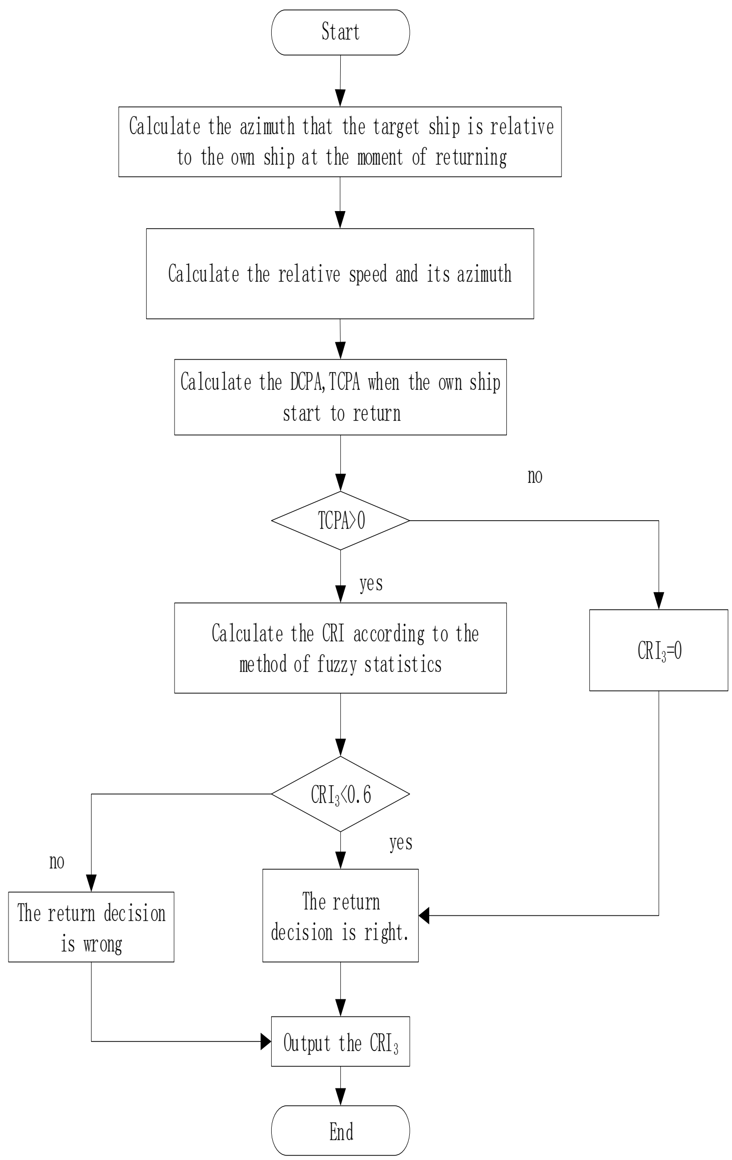


Figure 6. **The CRI before recovery course**

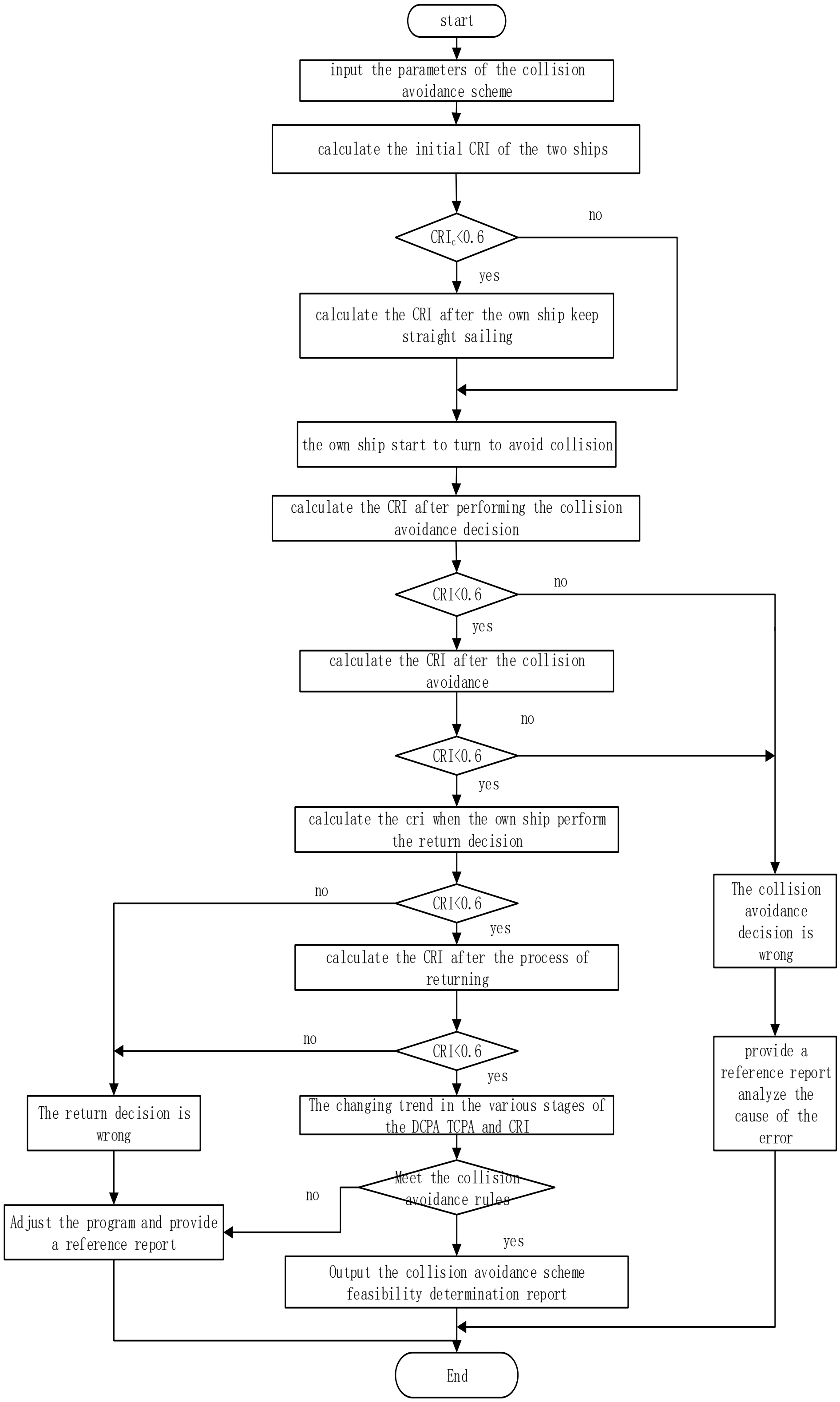


Figure 7 Vessel collision avoidance scheme feasibility Analysis flow chart

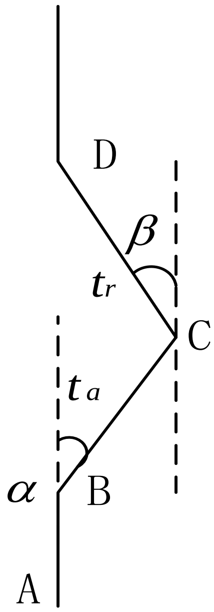
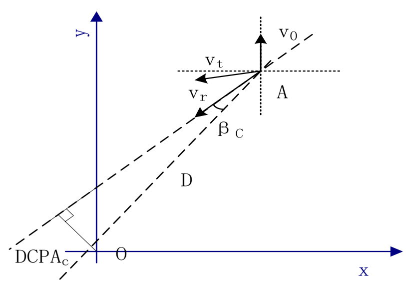
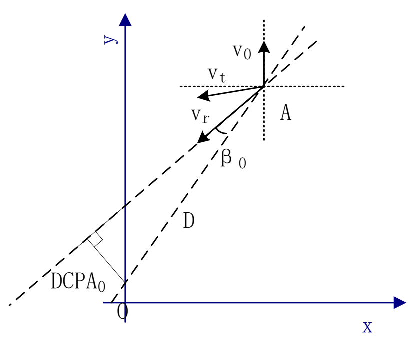


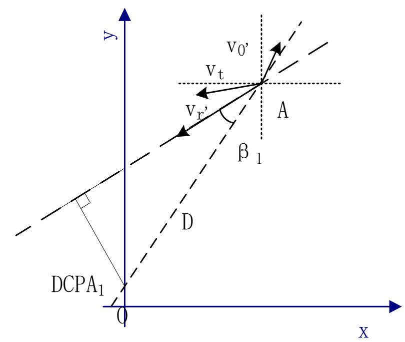
Figure 8 The diagram of collision avoidance process



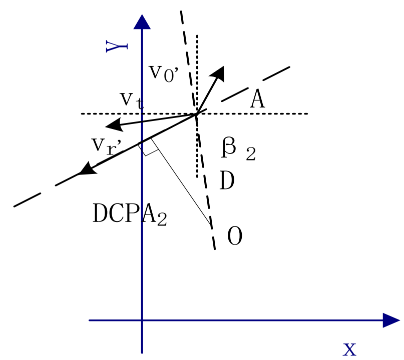
(1) The initial parameters



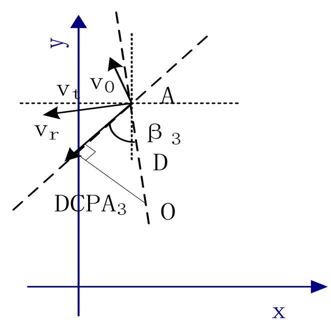
(2) Two vessels keep straight sailing



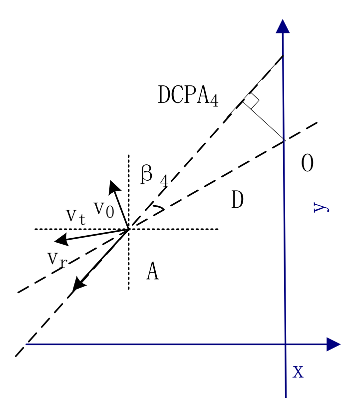
(3) Turn to avoid the collision



(4) at the end of the turning

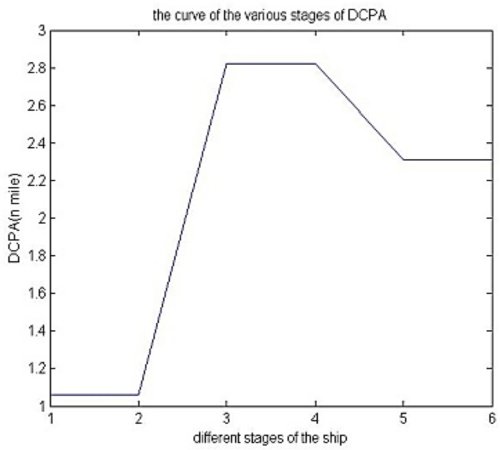


(5) During the return

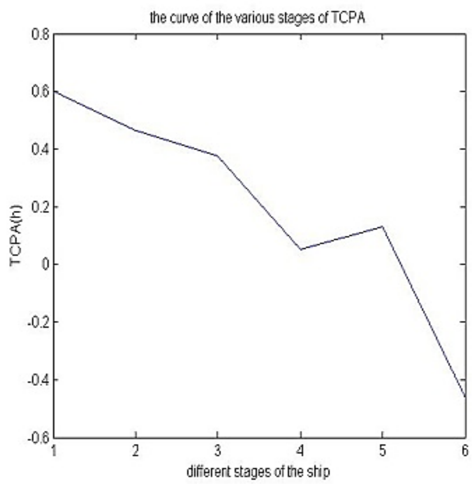


(6) At the end of the return

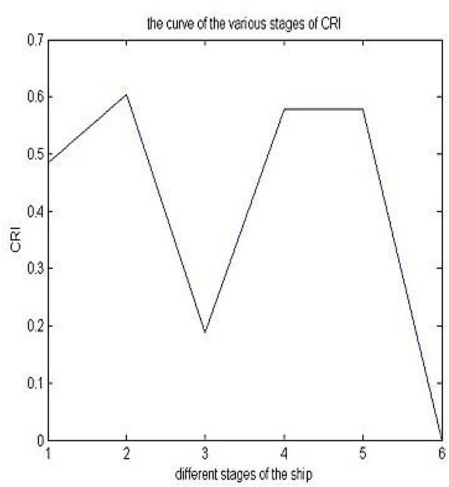
Figure 9 The stages schematic diagram of avoidance collision target vessel



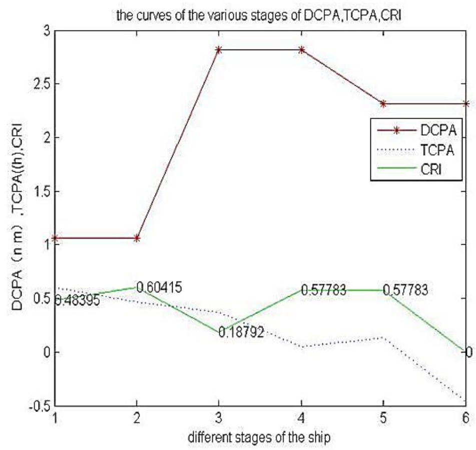
(1) DCPA curve of different stages



(2) TCPA curve of different stages



(3) CRI curve of different stage



(4) Comparison of each curve

Figure 10 the parameters curve graphs of collision avoidance target vessel in different stages

4 FEASIBILITY EVALUATION MODELING OF MULTI-VESSEL COLLISION AVOIDANCE

MULTI-vessel collision avoidance scheme for collision avoidance assessment is gotten based on the judgment of multi-vessels encounter situation by COLREGs. When the own vessel encounters multiple target vessels, sequence of collision avoidance would be given by decision model of multi-vessel collision risk degree and multiple single-vessel collision avoidance can be gotten. Many evaluation criteria by COLREGs are involved based on single-vessel collision avoidance in the implementation of multi-vessel collision avoidance scheme. On the other hand, during the process of multi-vessel collision avoidance evaluation, when the own vessel executes collision avoidance with target A, meanwhile, whether or not collision situation with target B should be assessed for own ship.

Therefore, the model of evaluation for the multi-vessel collision avoidance scheme don’t simply consider the doubling the number of stages, but also based on the COLREGs to evaluate the collision avoidance scheme.

According to the "International Regulations for Preventing Collisions in the (Szlapczynski & Szlapczynska, 2017), it divides vessels into the direct vessel and the give-way vessel that relative to the own vessel (Ahn, et.al, 2012). The collision avoidance decision and collision avoidance analysis are executed based on a prerequisite that own vessel is the give-way vessel. As shown in Figure 12. In the process of collision avoidance among own vessel and other target vessels, the collision avoidance assessment process is divided 6 stages due to the existence of resumption in vessel collision avoidance scheme. As a result, it will be 12 stages if the own vessel has a meeting with two target vessels. Assuming that own vessel meets with N target vessels and entering the relevant parameters

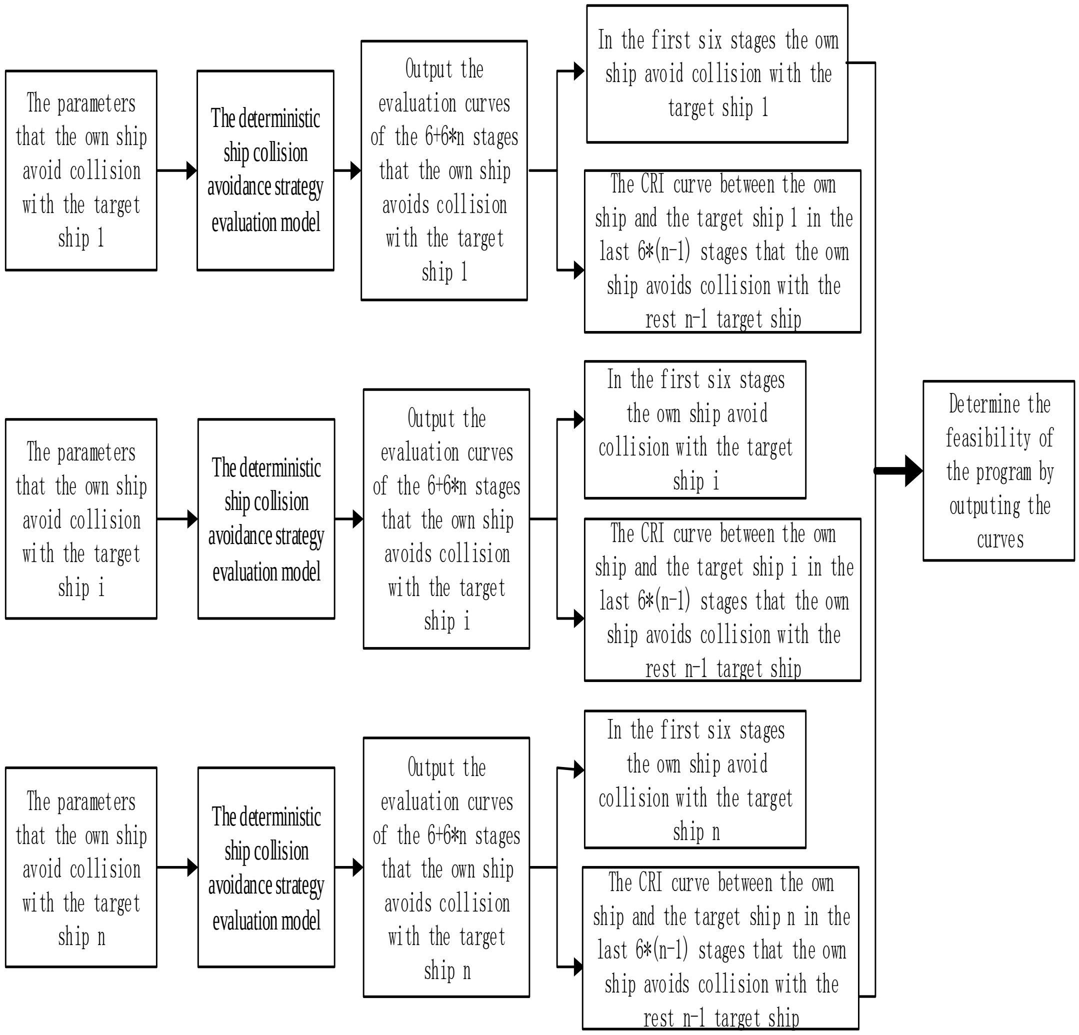
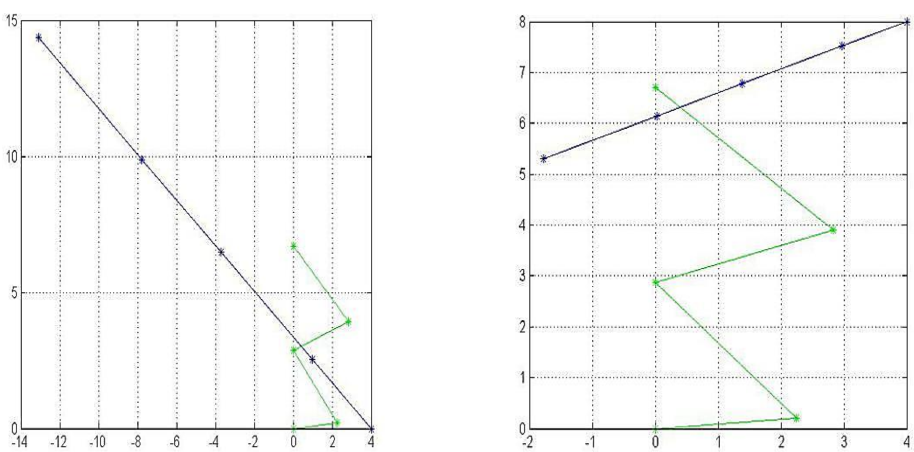


Figure 11 the diagram of feasibility assessment for multi-vessels collision avoidance scheme



(1) Track diagram which with the target vessel A

(2) Track diagram which with the target vessel B

Figure 12 Trajectory of own vessel collision avoidance target vessels of the i-th collision avoidance scheme, based on the ship's deterministic collision avoidance assessment model, the curve of the evaluation parameters in the process of collision avoidance of the i-th vessel is obtained, and the evaluation curve consists of N parts. The parameters evaluation curve of the first 6 stages is when the own vessel sail to avoid the first target vessel, and the last $6*(N-1)$ stages show with the other target vessels in the process of the collision avoidance.

The overall collision avoidance process and the evaluation curve for each collision avoidance will not be outputted until that all the collision avoidance plans for the vessel have finished, it is determined whether the own vessel's collision avoidance for the target vessel is feasible. In general, on the basis of the single-vessel evaluation model, the concrete realization process of the automatic collision avoidance assessment system is shown in Figure 12

4.1 Simulation Analysis of Multi-vessel Collision Avoidance

In order to be able to complete the simulation and analysis of the collision avoidance evaluation model, the situation of a specific three-vessel meeting would achieved and verified. The concrete parameters from AIS and APRA are as follows: the course of the own vessel is 0, the speed is 8, the latitude and longitude (0,0);the course of the target vessel A is 310, the speed is 14, the latitude and longitude (4,0);the course of the target vessel B is 245, the speed is 4, the latitude and longitude (4,8).After the own vessel and the target vessels have been running for some time, the own vessel 's collision avoidance action is as follows: the first collision avoidance time is 43.2min, the collision avoidance angle is 85°, and the return angle is 40°;the second collision avoidance time is 52.46min, the collision avoidance angle is 70°, and the return angle is 45.377.Based on the collision avoidance parameters of the own vessel and the target vessels, the motion process according to the division of each stages and the changes of course in the process of collision for the target vessels can be obtained.

Based on the collision avoidance information and collision avoidance parameters of the own vessel and each target vessels, the track diagram of the own vessel and target vessel A and B in the collision avoidance process is as shown below:

Based on the multi-vessel collision avoidance evaluation model, the feasibility and effectiveness of the collision avoidance solution of the above two collision avoidance methods are verified, which are as shown in the following figure: the simulation results show that the own vessel is first to avoid collision with the target vessel A and the collision risk of the two vessels in the initial state is as high as 0.87> 0.6. And after the collision avoidance with the target vessel A, the CRI drops to 0.53 <0.6,which means that the collision avoidance decision is correct. Then the two vessels continue to sail. At the end of the collision avoidance time, the TCPA is negative. The vessel at this time has passed the closest meeting of the two vessels, indicating that the two vessels at this stage are in no risk of collision. The turn of return is carried out after turning to the end of the collision. Meanwhile, the TCPA of vessels is always negative during the process of the return to the original route, which means that the own vessel has already passed the closest meeting between the two vessels of the above stage. This shows that the own vessel and the target vessel A’s collision decision-making is correct, so that the two vessels have effectively avoided the collision. Displayed by simulation graphic, the collision risk between the vessel and the target vessel A is 0 in the 6-11 stages (the collision between the own vessel and the target vessel B), which determines that the own vessel is under the safe condition in the collision with the target vessel A and B.

Based on the multi-vessel collision avoidance scheme evaluation model (LiuHongdan & LiuSheng, 2016), the feasibility and effectiveness of the collision avoidance solution in the above two collision avoidance plans are verified as shown in the following figure: The simulation results show that the own vessel is first to avoid collision with the target vessel A. And the collision risk index of the own vessel and the target vessel B has been below to 0.6 during this stage. When the own vessel completes the collision avoidance and the return to the original the original course, the CRI of the own vessel and the target vessel B is as high as 0.9> 0.6. Then the own vessel starts the collision avoidance with the target vessel B. The CRI of the own vessel with the target vessel B after the second collision turn reduced to 0.58 <0.6, which shows the success of the collision avoidance. As the result TCPA in this stage is negative, which means that the vessel at this time has passed the closest meeting of the two vessels, there is no risk for the vessels at this stage. The CRI of the two vessels after the return is 0.5 <0.6, which shows that the return decision is correct. When the own vessel finishes the collision avoidance again and sails back to the original route, the CRI among the own vessel, the target vessel A and the target vessel B turns into zero, the own vessel has successfully completed collision avoidance with two target vessels in the end.

The deterministic collision avoidance evaluation model has verified the effectiveness of the collision avoidance program for the own vessel in the case of the multi-vessel encounter. The results of the judgment are in line with the above diagram of the movement of each target vessel. And the validity of the multi-vessel collision avoidance evaluation model is also verified.

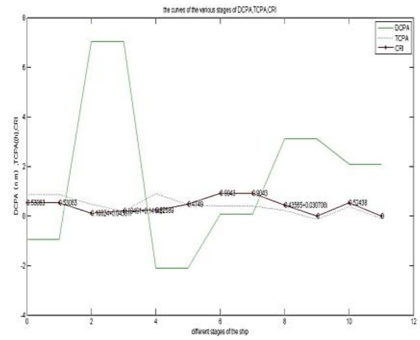


Figure 14 Evaluation of curve of for target A

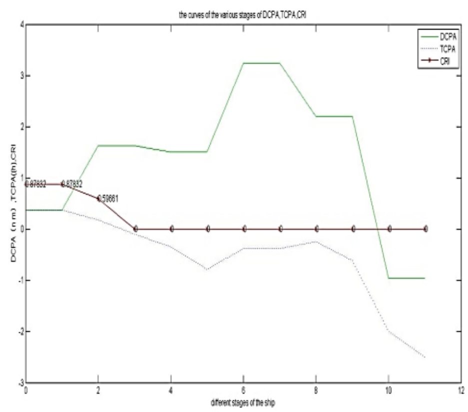


Figure 15 Evaluation of curve for target B

5 CONCLUSION

COMPARED to other collision avoidance evaluation model, the deterministic automatic vessel collision avoidance strategy evaluation model is based on the specific motion parameters of the own vessel and the target vessel, therefore, the deterministic is the most vital point for collision avoidance evaluation model; and then, the evaluation model proposed in the paper has a strong ability to expand, the single vessel collision avoidance evaluation model can be expanded to the model for the own vessel and two or more target vessels' collision avoidance evaluation. In addition, the implementation of the evaluation model is relatively simple due to entering the initial parameters of the two vessels and the collision avoidance decision-making program that the give-way vessel takes, the collision avoidance feasibility analysis curve and the program feasibility report can be obtained. Meanwhile, the application scope of the evaluation model is wide, which is suitable for the evaluation of vessel's intelligent collision avoidance simulation. Finally, the evaluation model is more comprehensive in the construction.

6 REFERENCES

Di Zhang, Xinping Yan & Jinfen Zhan (2016).Use of fuzzy rule-based evidential reasoning approach in the navigational risk assessment of inland waterway transportation systems .Safety Science, 23(1): 352-360

Foris Goerlandt, Jakub montewka &Vladimir Kuzmin (2015). A risk-informed ship collision alert system: Framework and application. Safety Science, 77:182-240.

Fukuda G, Shouji R (2017). Development of analytical method for finding the risk collision areas. 12th International Conference on Marine Navigation and safety of sea transportation. Gdynia (pp:12-19), Poland:TansNav.

Hansen, M.G., Jensen, T.K., Lehn-Schioler, T., Melchild, K., Rasmussen, F.M. & Ennemark, F(2013). Empirical vessel domain based on AIS data. J. Navig., 66:931-940.

IMO (1972). Convention on the international regulations for preventing collisions at sea (COLREGs).

JH Ahn, KP Rhee, & YJ You (2012).A study on the collision avoidance of a vessel using neural networks and fuzzy logic. Applied Ocean Research, 37:162-173.

Jiang Cong, Li Yuchen & Jian Yuan (2007, June). Study on Evaluation of Vessel Collision Avoidance[C]. Guangdong Maritime Advanced Forum, (pp:73-76).Guangzhou, China: Maritime Society.

Kaneko F (2002). Methods for probabilistic safety assessments of ships. Journal of marine science and technology.7:1-16.

Karahalios H (2014). The contribution of risk management in ship management: The case of ship collision. Safety Science, 63(3):104-114.

Lazarowska A (2014). Ant colony optimization based navigational decision support system. Procedia Computer Science, 35: 1013-1022.

Liu Dexin, Wu Zhaolin & Jia Chuanying (2004). Decision Model of the Target vessel motion parameters and the DCPA, TCPA. Journal of Dalian Maritime University, 30:22-25.

Liu Dongdong, SHI Guoyou & LI Weifeng, (2018).Decision support of collision avoidance based on shortest avoidance distance and collision risk Journal of Shanghai Maritime University. 39(1):13-16.

Liu Yuhong, Hu Shenping (2005).An Evaluation System for Single-Target Vessel Collision Avoidance Based on Data Fusion. China Sailing, 4:40-45.

LiuHongdan, LiuSheng (2016).Study and Simulation on Automation Multi-ships Collision Avoidance Strategy. Journal of Computational and Theoretical Nanoscience, 13:194-210.

Perera L, Carvalho J & Soares C (2011). Fuzzy logic based decision making system for collision avoidance of ocean navigation under critical collision conditions. Journal of marine science and technology, 16:84-99.

Q Xu, X Meng, N Wang, (Eds.) (2009, July). Vessel Manipulation Evaluation System. International Conference on Measuring Technolog(pp: :859-862).

Szlapczynski, Rafa, Szlapczynska, Joanna (2017). A method of determining and visualizing safe motion parameters of a ship navigating in restricted waters. Ocean Engineering, 129:363-373.

T. Statheros, G. Howells & K. McDonald-Maier (2008). Autonomous vessel collision avoidance navigation concepts, technologies and techniques. J. Navig., 61:129-142.

Wang Delong, Ren Hongxiang & Xiao Fangbing (2015). Auto Assessment System for Single-Target Collision Avoidance on Vessel Handling Simulator. China Sailing, 38:44-49.

Wang Delong, Ren Hongxiang & Xiao Fangbing (2015). Automatic Evaluation System for Single-Vessel Collision Avoidance of Vessel Maneuvering Simulator. China Sailing, 38:44-48.

Wu Zhaolin, Wang Fengchen (1986). A Statistical Study on the Collision Avoidance Behavior at Sea. China Sailing, 2:62-70.

XuWen, HuJiang-qiang & YinJ ian-chuan (2017). Composite evaluation of ship collision risk index based on fuzzy theory. Ship science and rechnology, 39(7):79-83.

Yang Bing, Gao Fuping, Jeng Dongsheng. (2018) Failure mode and dynamic response of a double-sided slope with high water content of soil. Journal of Mountain Science, 15(4): 859-870.

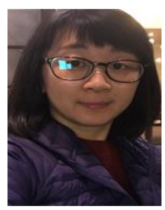
Zhang D, Yan X & Yang, Z (2013). Incorporation of formal safety assessment and Bayesian Network in navigational risk estimation of Yangtze River. Reliab. Eng. Syst. Saf. 118:93-105.

Zhu Zhengzhong, Wu Xi & Shi Pingan (2010, August). Evaluation of Vessel Collision Avoidance Based on TOPSIS. Seminar on Marine Vessel Collision Avoidance for Marine Driving Committee, (pp:68-72) .China :Maritime Society.

7 NOTES ON CONTRIBUTORS

Liu Hongdan was born in Qiqihaer city, Heilongjiang Province, China in 1983. She is now a lecture at college of automation in the Harbin Engineering University; her current research interests include intelligent ship, ship automsatic navigation, Ship's course control, digital image processing.

Liu Qi was born in Shuangyashan City, Heilongjiang Province, China in 1994.She graduated from the Automation College of Harbin Engineering University in 2016. She is currently pursuing the master's degree in engineering in Control Science and Engineering at Harbin Engineering University. Her research interests include intelligent control theory and application, intelligent robot technology.



Sun Rong was born in Dalian City, Shandong Province, China in 1978, she got her PhD in engineering in 2003. Now she is the associate professor at college of automation in the Harbin Engineering University; her research direction is control theory and control engineering. More than 10 papers have been published in some journals.