Research and Development of Collision Risk Decision Method for Safe Navigation and Its Verification

Satoru KUWAHARA*, Haruka NISHIMURA*, Kazuya NAKAGAWA**, Makoto YOSHINAGA**, Syuichi ISEKI***, Ryo YOSHIDA***, Tadashige HAKOYAMA****, Koji KUTSUNA*****, Jun NAKAMURA*****

1. INTRODUCTION

Innovation of ICT technologies has advanced rapidly in recent years, and research and development of new technologies using big data has been actively pursued in various industries, including the automobile industry. In the marine transportation industry, joint industry governmental-academia research and development of new technologies using big data has also been promoted internationally, especially in Europe, and the impact of that innovation has spread to the marine transportation business.

In Japan as well, industry, government and academia have mobilized their total capabilities to conduct research and development on technologies using ship big data, which will be an important factor in future development, in order to strengthen the international competitiveness of the marine transportation industry in Japan, with a view to finding opportunities for new marine transportation businesses in line with this global trend.

As part of these efforts, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) positioned the year 2016 as the "first year of the productivity revolution," and the Ministry's Maritime Bureau has been promoting a "Maritime Productivity Revolution" initiative (commonly called "i-Shipping"). In the field of ship operation in i-Shipping, the Bureau provided subsidies for a total of eight technical development projects, including the development of a monitoring technology for the hull structure by FY 2017, with the aim of improving the safety and efficiency of ship operation by supporting research and development of advanced devices and systems utilizing technologies such as IoT (Internet of Things) for ships and marine devices and big data analysis.

This paper report introduces the efforts of Nippon Yusen Kabushiki Kaisha (NYK Line), MTI Co., Ltd., Japan Marine Science Inc., Furuno Electric Co., Ltd., Japan Radio Co., Ltd.,(JRC) and Tokyo Keiki Inc., which are participating in a "study on collision risk judgment and autonomous operation of vessels (Field: Operation support using a rocking and operation simulator)," which is one of the projects selected for the initiative (subsidized research and development projects for advanced safe ship technologies).

The significance of work in this study is to secure safety in navigation against risks associated with the recent trends of larger and faster ships, more congested ship traffic and fewer crew, and to reduce the work burden. To achieve these purposes, three topics were studied: "I. Research and development of a collision risk decision method," "II. Research and development concerning autonomous ship," and "III. Navigation support tool using computer vision." This report introduces the results of "I. Research and development of a collision risk decision method."

2. BACKGROUND OF RESEARCH AND DEVELOPMENT OF COLLISION RISK DECISION METHOD

Post-accident investigations have found that insufficient watch by navigation officers accounts for almost half of ship accidents. Therefore, accurate identification of ships at risk of collision in collision avoidance navigation is considered to be the most important task.

As a risk level index for collision between one's own ship and another ship, it is a common practice to give the master / navigation officer a risk level index using the distance of closest point of approach (DCPA) and the time to closest point of

* Japan Marine Science Inc.
** Furuno Electric Co., Ltd.
*** Japan Radio Co., Ltd.
**** Tokyo Keiki Inc.
***** MTI Co., Ltd.

approach (TCPA) after calculating the closest point approach (CPA) with ARPA installed on the marine radar.

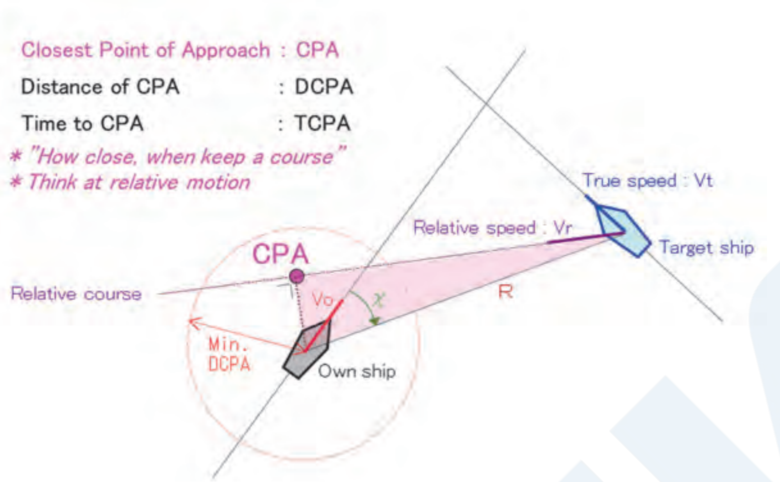


Figure 1　Information based on close point of approach

However, the risk level index using DCPA/TCPA does not consider factors such as encounter situations between the own ship and another ship. In congested waters such as Tokyo Bay and the Singapore Straits, many ships are judged as dangerous based only on DCPA/TCPA settings, and alarms are frequently issued. As a result, the following problems arise.

- Difficult to monitor ships according to collision risk
- Cross-check is difficult between compare visual information and DCPA/CPA information
- Reduced attention of master / navigation officer to alerts

In contrast, some past studies mentioned methods for indicating an area where a ship may collide with another ship (collision risk area), such as PAD (Predicted Area of Danger), DAC (Dangerous Area of Collision) or OZT (Obstacle Zone by Target), which means a zone of obstruction by another ship.

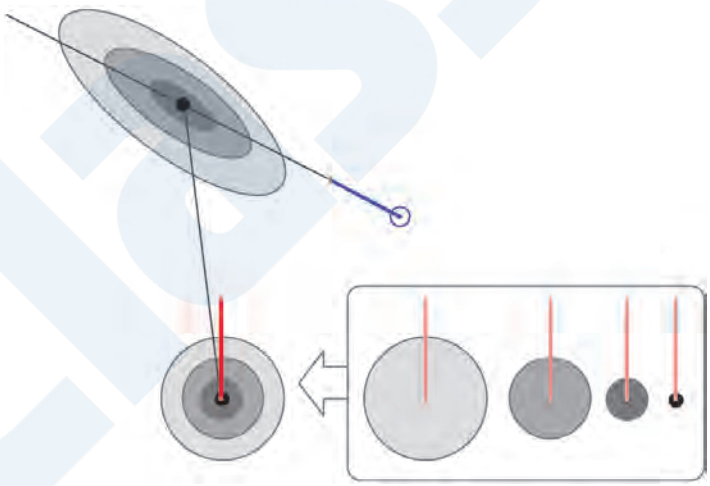


Figure 2　Illustration of collision risk area

Displaying a collision risk area enables the master / navigation officer to determine the risk of collision in the form of a plane rather than a dot, and would be very helpful for formulating a collision avoidance navigation plan by showing the master / navigation officer the area where the ship may collide with another ship. However, as one problem, it is difficult to use this method as a reference for formulating a collision avoidance navigation plan because the ship’s course may be filled with collision risk areas in congested waters such as the mouth of Tokyo Bay mouth and the Singapore Straits.

In order to reduce collision accidents in spite of this problem, it is important to identify the characteristics of human cognition of collision risk, appropriately reflect those characteristics in the functions of machines and enable humans to use those functions appropriately. The following figure summarizes the characteristics and comparison of a machine and a human being in terms of collision risk cognition.

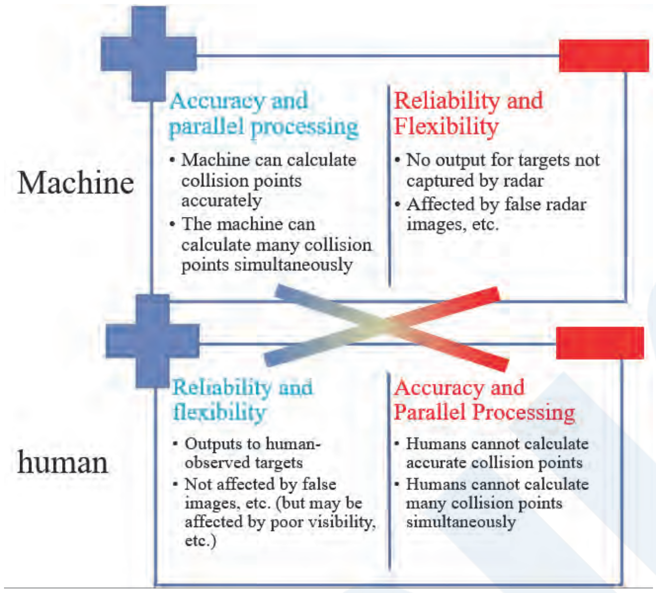


Figure 3　Comparison of collision risk cognition by machine and human

In order to solve the problem described above, this study presents the risk of collision between a ship and another ship in the form of an index in a manner that matches the master / navigation officer’s sense of risk, and establishes a means of notifying the master/navigation officer of a possible collision and a collision avoidance policy in a manner that enables the master/navigation officer to make a decision intuitively based on this index. Furthermore, in this study, the method for displaying an area where the ship and another ship may collide was improved to make the area closer to what the master / navigation officer recognizes as a collision risk area, and the problem that congested waters are filled with collision risk areas, as described above, was also improved.

In this study, over five years, more than fifty acting masters and navigation officers from NYK Line and over twenty students from Tokyo University of Marine Science and Technology and Kobe University participated as subjects, and data for developing a collision risk level index were obtained in order to validate the developed devices. The following sections describe the specific contents of the research and development by Furuno Electric, Japan Radio and Tokyo Keiki, which developed collision risk level indicators and devices, and an analysis by Japan Marine Science, which led an experiment to verify the effects of the developed devices.

3.　TECHNOLOGICAL DEVELOPMENT

3.1　Technological Development by Furuno Electric Co., Ltd.

In safe operation of a ship, it is important for the master / navigation officer to notice any collision risks present around the ship without fail and make decisions on operation at the correct timing. However, during navigation in actual congested waters, masters / navigation officers must handle and make judgments on so many ships that they may overlook or be late in recognizing collision risks. In addition, in encounter situations involving any of a large number of ships, it is not sufficient simply to notice a collision risk, since it is difficult to take appropriate avoidance action if the operator does not also grasp the situation immediately. A collision risk index and a collision risk display system that were established to solve these problems are introduced in this section.

3.1.1　Establishment of Collision Risk Index

To establish a collision risk index based on the master / navigation officer’s sense of collision risk, an approach consisting of three stages was implemented: first, “Digitalization of an experienced master / navigation officer’s sense of risk,” second, “Analysis of data on the sense of risk,” and third, “Development of an algorithm for collision risk alarm.” These three stages are explained below.

3.1.1.1 Digitalization of Experienced Master / navigation officer's Sense of Risk

An experienced master / navigation officer can operate a ship safely, even in congested waters, by appropriately understanding the situation. It is generally thought that the short-term memory capacity of humans is limited to about 4 to 5 pieces of information [1]. Given this limited memory capacity, the main components of the maritime skills required to ensure safe navigation are considered to include prioritization based on an appropriate sense of collision risk. Even assuming collision risk warnings are given to assist watches, the master / navigation officer may be confused by excessive information if multiple collision risk warnings are given without appropriately setting priorities in congested waters. To solve this problem, in this study, technological development was conducted with the aim of establishing a collision risk warning algorithm that assigns appropriate priorities by digitalizing the sense of collision risk of experienced masters / navigation officers.

First, data were prepared for the timing when risks are recognized, the types of ships recognized as risks and the level of risk. In digitalization, a tablet-type data acquisition system for the sense of risk (Fig. 4) was newly developed.

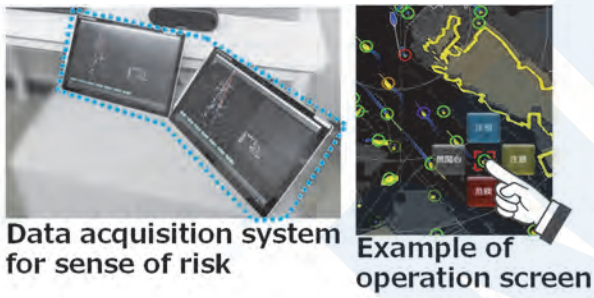


Figure 4 Developed data acquisition system for sense of risk

The data acquisition system for the sense of risk, which provides four risk levels, enables the user to enter the collision risk that the master / navigation officer senses in surrounding ships at the timing when the risk level changes. The definitions of the risk levels are shown below.

- Safe (no concern): No sense of risk in the subject ship.
- Close observation: Movement of the subject ship is observed occasionally.
- Attention: Movement of the subject ship is observed constantly.
- Dangerous: Action is taken to avoid the subject ship.

The risk level is set to "Safe" for a ship in the initial state, and one of the risk levels in the four stages above is always set for the subject ship.

Using the developed data acquisition system for the sense of risk, an experiment was conducted to acquire data on experienced master / navigation officers' sense of risk under various scenarios of navigation in congested waters in a simulated ship operation environment (reproduced in visual images from the bridge and on navigation devices at Japan Marine Science Inc.) (Fig. 5).

Figure 5 Experiment to acquire experienced masters / navigation officers' sense of risk

Table 1 shows the masters / navigation officers who participated in the experiment. In each fiscal year, multiple scenarios for congested waters such as the Kanmon Straits, Kii Channel and waters off the coast of the Oshima Island were used, and data on the sense of risk were acquired from a total of 20 people (16 captains, 3 first mates, 1 second mate).

Table 1 Crew with certificate of competency in seamanship who participated in data acquisition experiment for sense of risk

	FY 2016	FY 2017	FY 2018	Total
Captain	6 [persons]	6 [persons]	4 [persons]	16 [persons]
First mate	1 [person]	-	2 [persons]	3 [persons]
Second mate	1 [person]	-	-	1 [person]

3.1.1.2 Analysis of Sense of Risk Data

The following describes an analysis of the data on the sense of risk conducted to create an algorithm for the sense of collision risk of experienced masters / navigation officers. The analysis was carried out using a calculation model for the collision risk level [2] (bumper model) defined by the passing distance in the bow-stern direction and the port-starboard direction around the ship and the time to closest point of approach (TCPA). The distances (a, b and c) in the bow-stern direction and the port-starboard direction and the allowance time (weight) W_{tcpa} for the TCPA were considered as variable parameters, and the model geometries that best represent the individual masters / navigation officers' sense of collision risk were compared.

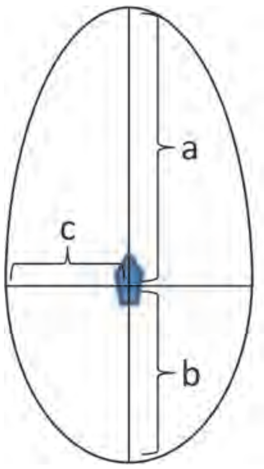
The rates of satisfying warning requests and satisfying non-warning requests are defined by formulas (1) and (2) below.

$$\text{Rate of satisfying warning request} = \frac{\mathrm{TP}}{(\mathrm{TP+FN})}, \tag{1}$$

$$\text{Rate of satisfying non-warning request} = \frac{\mathrm{TN}}{(\mathrm{TN+FP})}. \tag{2}$$

In Formula (1) and (2), TP, TN, FN, FP represents the combination patterns of the judgment by an experienced master / navigation officer and the result of the judgment based on the bumper model as below.

- If the judgment by an experienced master / navigation officer is "Attention" or higher, and the result of the judgment based on the bumper model is also "Attention" or higher: TP (True-Positive)
- If the judgment by an experienced master / navigation officer is "Close observation" or lower, and the result of the judgment based on the bumper model is also "Close observation" or lower: TN (True-Negative)
- If the judgment by an experienced master / navigation officer is "Attention" or higher, and the result of the judgment based on the bumper model is "Close observation" or lower: FN (False-Negative)
- If the judgment by an experienced master / navigation officer is "Close observation" or lower, and the result of the judgment based on the bumper model is "Attention" or higher: FP (False-Positive)



Parameter	Setting range
a. Distance in bow direction (NM)	0.9 to 2.1
b. Distance in stern direction (NM)	0.6 to 1.4
c. Distance in port-starboard direction (NM)	0.3 to 0.7
W_{tcpa} (min)	6 to 15

Figure 6　Bumper model and adjustment parameters

An ROC analysis (Receiver Operating Characteristic analysis) was conducted by plotting the values of the rates of satisfying warning requests and satisfying non-warning request obtained by formulas (1) and (2) while changing the adjustment parameters for the bumper model shown in Fig. 6. Since there were more than two variable parameters, a group of points on the outermost side from the origin (outermost points) was chosen from the points plotted on a two-dimensional plane of the rate of satisfying warning request and the/ -rate of satisfying non-warning request, as shown in Fig. 7, and was then used to draw an ROC curve. The ROC curve can be regarded as the results extracted from the parameter group adjusted by the bumper model so as to best represent an experienced master / navigation officer's sense of collision risk.

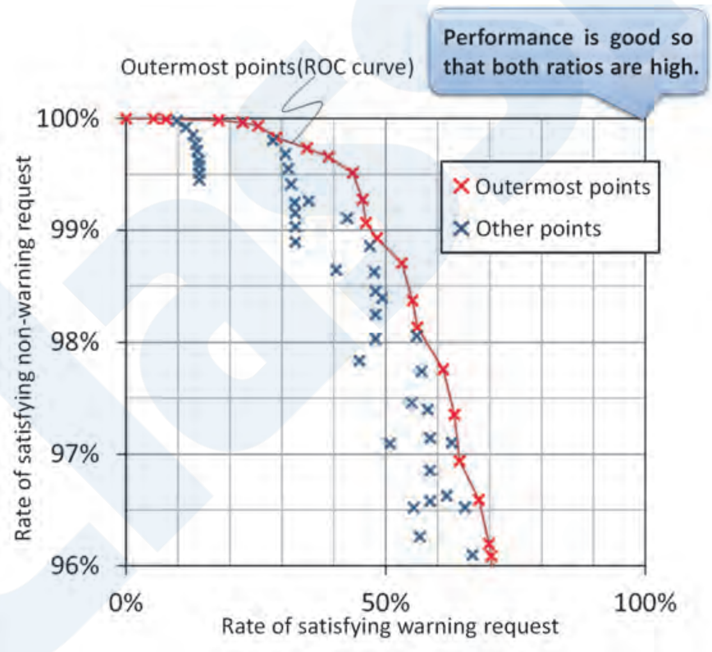


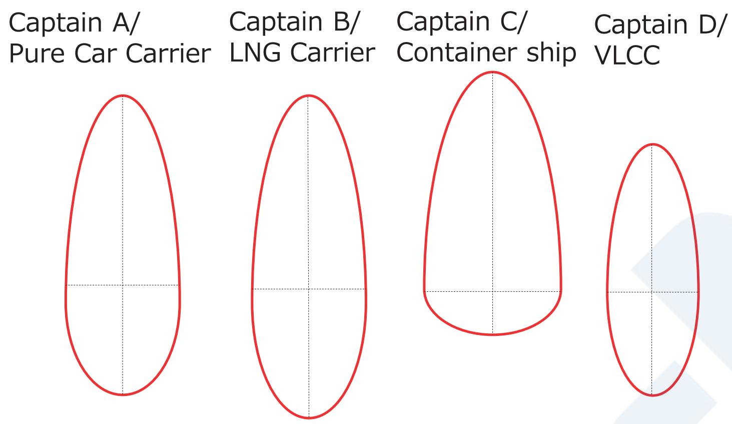
Figure 7　ROC curve

Figure 8 shows the bumper geometry for each master / navigation officer at the highest rate of satisfying warning requests in a range of rates of satisfying non-warning requests of 98 % or more. Figure 8 shows examples of the bumper geometries of the four captains, together with the different types of ships they operate. This result shows that the master / navigation officers' sense of collision risk includes many differences depending on the individual or ship type. The figure indicates that their senses of risk varied widely, especially for risk at the ship's stern. The results also indicated that some master / navigation officers, like captain D, may consider the entire bumper area to be small and the W_{tcpa} value to be short.

This result indicates that it will be necessary to construct a collision risk index as an algorithm that the user can adjust, while considering an algorithm reflecting the sense of collision risk of various masters / navigation officers depending on the individual sense and ship type, as well as variations in the sense of collision risk of the masters / navigation officers.

3.1.1.3 Development of Algorithm for Collision Risk Alarm

A new collision risk index was formulated based on the results of the analysis of the risk sense data described in the preceding section and a multifaceted analysis, and an algorithm for issuing alarms according to the risk of collision with another ship was established. In this algorithm, an alarm algorithm that can adapt to variations in the sense of risk of masters / navigation officers, as described in the preceding section, was selected by developing more advanced adjustment parameters. Figure 9 shows an example of the display screen of a warning system using the algorithm. The system achieves a warning function by presenting risk levels by OZT display and color/sound. The results of an evaluation with a simulator using the established algorithm are shown below.



	Bow [NM]	Stern [NM]	Port-starboard [NM]	W_{tcpa} [min]
Captain A	1.8	0.8	0.5	12
Captain B	1.8	1.2	0.5	12
Captain C	1.9	0.4	0.6	12
Captain D	1.3	0.9	0.4	7

Figure 8　Master / navigation officers' sense of risk (visualized using bumper model)

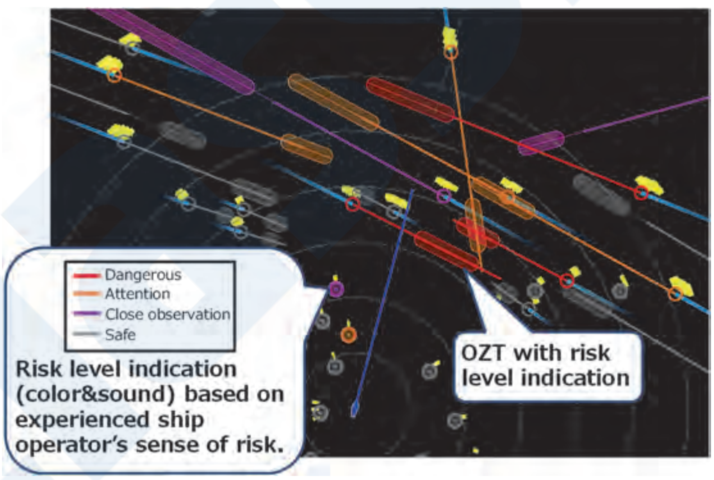


Figure 9　Warning system with risk levels and OZT display

Table 2 shows comments obtained in interviews with subjects who used the established warning system in a simulator test under congested water navigation scenarios. The comments are classified into positive and negative comments about the warning function. The positive comments show that the established warning system prevents overlooking risks and ensures recognition of changes in other ships' behaviors. The timing of issuing warnings was also rated highly. As negative comments, simply presenting the priorities of ships requiring attention by using risk levels did not completely prevent confusion of the master / navigation officer when the system was used in congested waters where a number of ships requiring attention can be seen.

Table 2　Evaluation and comments on collision risk warning algorithm

Positive/Negative	Content of comment
Positive	• In this scenario, the areas where the ship can navigate are limited so strictly that the master / navigation officer has no choice but to pass the acceptable area. The situation will not change even if a warning is issued, but a warning is necessary because it makes it possible to prepare ourselves. (Captain A) • The system made me aware of a target that became dangerous due to an abrupt slowdown. (Captain B) • A CPA warning is a scenario in which an alarm should be sounded continuously, but the new warning was issued appropriately (first mate D, third mate F). • The system made me aware of a meeting vessel that I overlooked in visual watch (junior third mate G, junior third mate H). • The system made me aware of a heading change by another ship. (Captain I, Captain J)
Negative	• So many targets are described as “Danger” or “Requiring attention” that the situation sometimes exceeded my cognition ability. (first mate E) • If the number of “Close observation” targets increases, it is difficult to understand. The risk level “Close observation” may be unnecessary. (first mate D)

3.1.2　Establishment of Collision Risk Indication

The results of the evaluation of the collision risk warning algorithm described in the preceding section indicated a weakness in the support function for understanding the surroundings in congested waters if only the risk level for each ship is presented. Therefore, an indication function was established to compensate for this weakness.

In the situation shown in Fig. 9, the large number of ships requiring attention confused the master / navigation officer. As shown in Fig. 9, the risk level for the target ship is displayed in the same color as the OZT display color, but in congested waters like those in this experiment, a large number of ships other than safe ships are displayed simultaneously. Therefore, the display system was unsuitable for studying how to avoid collisions with these many ships.

To solve this problem, the following improvements were made in the collision risk indication.

① For the width of the OZT display (perpendicular direction from the course of another ship), the display area is expanded, and the apex of the obstacle zone is set at the ship’s position at which the other ship passes safely at an arbitrary distance in the ship’s bow direction, or the ship’s position at which the other ship passes safely at an arbitrary distance in the ship’s stern direction (Fig. 10).

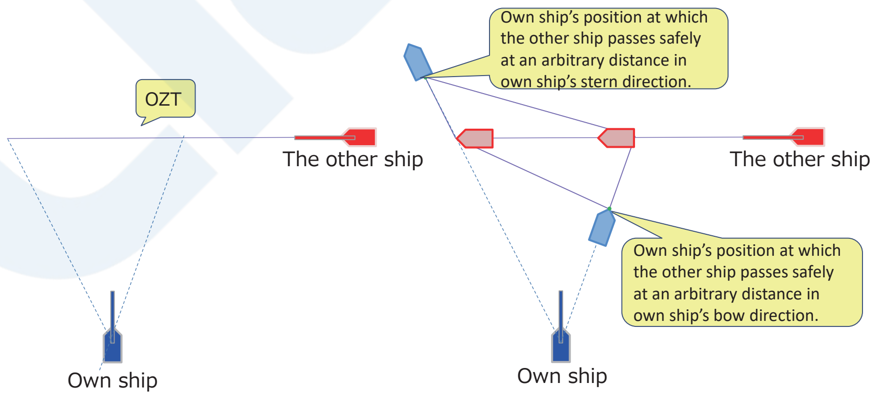


Figure 10　Expansion of display

② The zone calculation in ① is executed with two distance settings, the distance at which to keep watch for any approach to the ship and the hull length of the own ship and another ship, and the two obtained zones are expressed as the approach zone and the collision zone, respectively (Fig. 11).

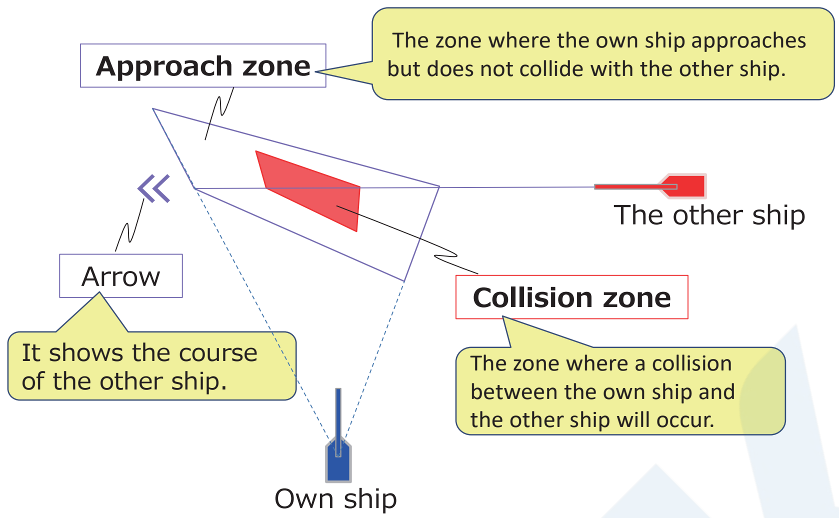


Figure 11　Display of collision risk indications (approach zone and collision zone)

③　The risk levels are indicated by the icon of the other ship and the color of the collision zone.

These improvements enable a separate display of the zone where a collision between the own ship and the other ship will occur (collision zone) and the zone where the own ship approaches but does not collide with the other ship (approach zone). The collision risk level is indicated by the collision zone display color so that a route can be selected while considering the approach zone caused by multiple ships from a panoramic point of view. The collision risk levels of individual ships are indicated in collision zone display colors that are shown for relatively small zone as a support function for prevention of overlooking individual ships subject to collision risk warnings and collision avoidance decisions.

Figure 12 shows an example of a display of the collision risk indications established in this project. In comparison with the collision risk levels indicated by the OZT display colors in Fig. 9, the system indicates fewer areas where “navigation seems impossible” according to display zone. The collision risk level display also sufficiently represents the collision risks for individual ships. As indicated by the red broken line in the figure, by using the display, the user can easily locate areas which are congested with ships by viewing the collision risk indications caused by multiple ships from a panoramic perspective. Areas with fewer collision risk indications can also be grasped easily, as indicated by the yellow broken line in the figure. This has made it possible to provide, at an early timing, not only the information necessary for avoiding collisions with individual ships, but also the information necessary for selecting routes for the risks that will be encountered in the future.

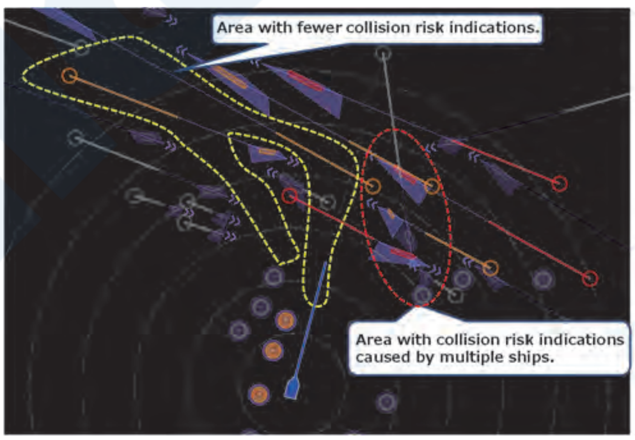


Figure 12　Collision risk indications established for this system

3.1.3　Summary of Efforts by Furuno Electric Co., Ltd.

This section 3.1 has introduced an overview of the collision risk index and collision risk indication developed by Furuno Electric. This high effectiveness of this technology in supporting decision-making for ship operation has already been confirmed through a number of simulation tests, and it is expected that the number of ship collisions will decrease and the burden of watch duties will be reduced. In the future, the company is targeting practical application of this technology as a "collision warning function and collision avoidance support display function" after conducting a demonstration experiment in which master / navigation officers will evaluate the technology using real ships and demonstrating compliance with the Guidelines for Safe Design of Automated Ship Operation to improve the effectiveness and practicability of the functions.

3.2 Technological Development by JRC

3.2.1 Collision Risk Index

JRC studied a collision risk index that matches the sense of risk of actual navigation officers to replace DCPA/TCPA based on "Nagasawa's collision risk levels" [2]. In Nagasawa's collision risk levels, the passing distance with other ship that the master / navigation officer judges as safe is defined by an elliptic area, as shown in Fig. 13. The size of this ellipse (minor radius a, major radius b) and the distances in the bow-stern direction and the port-starboard direction are represented as functions using the length, speed and course of own and other ship as parameters. Since it is thought that failure to secure this passing distance will place a psychological burden on the master / navigation officer, the risk level is calculated based on the magnitude of the intrusion level.

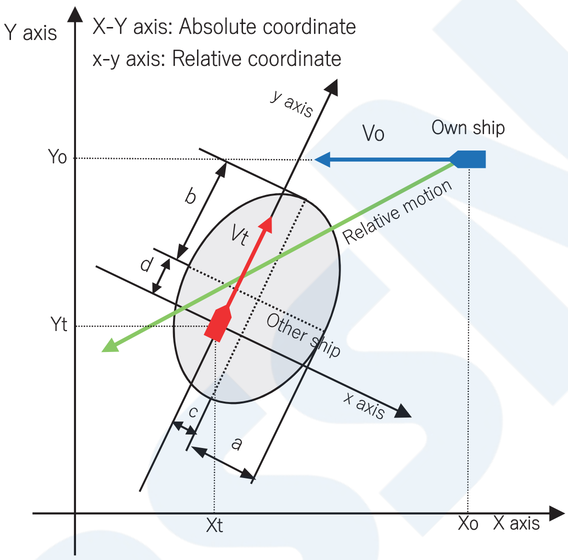


Figure 13　Concept of safe passing distance

a, *b*, *c*, *d*: Passing distance parameters
Vo: Speed of own ship (m/s)
Vt: Speed of other ship (m/s)

For the collision risk index R, the values of the risk levels *Rx* and *Ry* in the port-starboard direction and the bow-stern direction, respectively, from the intersection point between the x-y coordinate axis and the relative motion vector around the other ship are found, as shown in Fig.14, and the larger value is adopted as the risk level. To evaluate the time-based allowance, weighting is performed by using the ratio of the time to the closest point of approach (*Tcpa*) to a certain allowance time (*Wtcpa*).

$$\text{Collision risk index } R = Max\left(Rx,\ \ Ry\right) \times \left(1 - \frac{Tcpa}{Wtcpa}\right) \geq 0$$

Tcpa: Time to closest point of approach
Wtcpa: Allowance time (weighting factor)

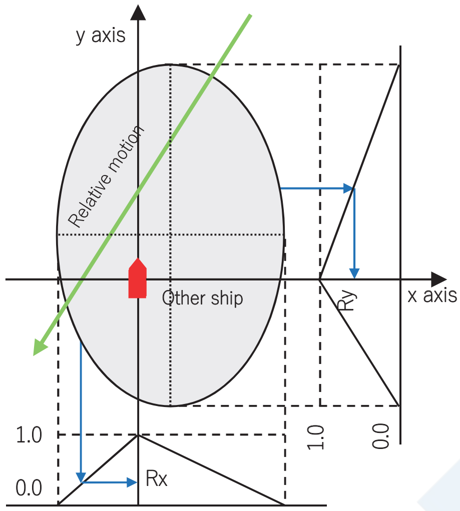


Figure 14　Collision risk index calculation model

Based on this index, the parameters for calculating the collision risk index were adjusted using data on collision risk judgment collected from master / navigation officers in a ship operation simulation test and the results of interviews conducted after the test.

Since the collision risk index is represented by a numerical value from 0.0 to 1.0 (where 1.0 represents the most dangerous situation), the thresholds shown in Fig. 15 are set, and the master / navigation officer is notified of the collision risk by using the following three levels.

- Danger (D): A ship that immediately requires collision avoidance navigation.
- Warning (W): A ship that requires caution as a ship that does not require immediate collision avoidance navigation, but may require action in the future.
- Safe (S): Ships other than the above.

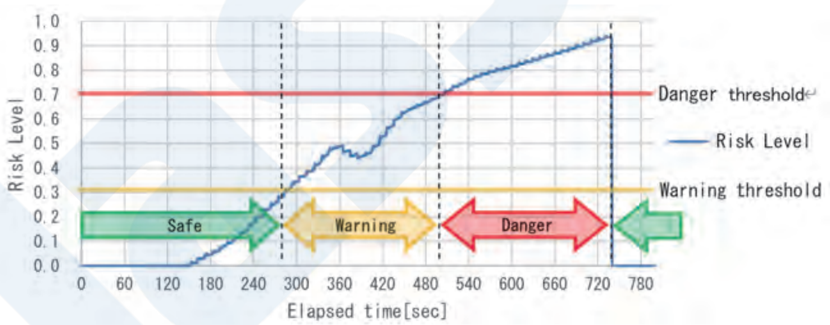
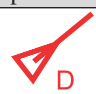


Figure 15　Concept of thresholds

In this way, the results of judgments on other ships by the collision risk index are used to issue warnings concerning dangerous ships and ships requiring caution. The results of these judgments are represented by the symbol color of the AIS target, as shown in Table 3.

Table 3　Method for displaying risk level judgments

Risk level	Identification number	Symbol color	Effect	Example of display
Danger	D + target number	Red	Blinking	
Warning	W + target number	Orange	Blinking	
Safe	S + target number	Green	None	

A prototype was developed to verify the effect of the collision risk index. The index was incorporated in the radar system, which is a typical support device for collision avoidance. The results of the ship operation simulation test confirmed that the Danger and Warning alerts expressed by the collision risk index were closer to the navigation officers' sense of risk than DCPA/TCPA for ships approaching in various encounter situations where collision was possible.

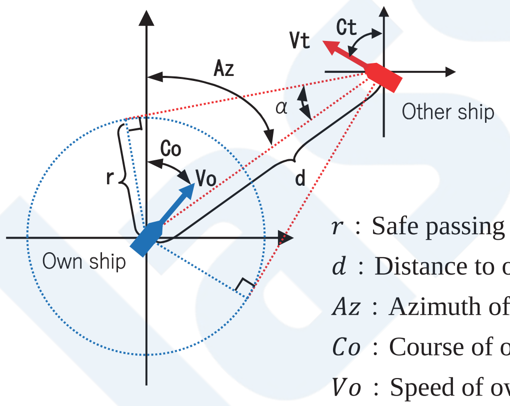
Study of the practical application of this collision risk index will be necessary in the future. Although the collision risk index was incorporated in the radar system as the prototype, IMO rules require the use DCPA/TCPA alarms in radar. Thus, incorporation of the collision risk index in radar appears to be difficult under these circumstances. To enable early practical use, it will be necessary to consider incorporating the index in a device which is not subject to the above-mentioned IMO requirement. Since it is thought that a collision avoidance navigation support system that integrates data acquired by cameras and the like in addition to a radar and AIS will be developed for autonomous ship in the future, it is desirable to study practical application of the index in that type of integrated target display device.

3.2.2 Collision Risk Area

For the display method of the collision risk area, we first considered using OZT (Obstacle Zone by Target) [3], which was devised by Professor Emeritus Imazu Hayama of Tokyo University of Marine Science and Technology. OZT indicates a course where the navigation of a ship may be obstructed by other ship. Here, it means the area in which the distance to other ship is within the minimum safe passing distance r, that is, when the distance to closest point of approach (DCPA) of the other ship satisfies the following condition.

$$DCPA \leq r$$

A course in which $DCPA = r$ between own ship and other ship is defined as a collision course Co. The method of calculating the collision course is shown in Fig. 16.



r : Safe passing distance
d : Distance to other ship
Az : Azimuth of other ship
Co : Course of own ship (collision course)
Vo : Speed of own ship
Ct : Course of other ship
Vt : Speed of other ship
α : Angle of the tangent
$(\alpha = \sin^{-1} r/d)$ (3)

Figure 16 Collision course calculation diagram

In the above variable, the following relation formula holds.

$$\frac{\sin(Az \pm \alpha - Co)}{Vt} = \frac{\sin(Az \pm \alpha - Ct)}{Vo}$$

Based on this, a collision course Co in which $DCPA = r$ can calculate as follows.

$$Co = Az \pm \alpha - \sin^{-1}\left\{\frac{Vt}{Vo}\sin(Az \pm \alpha - Ct)\right\} \quad (4)$$

The dangerous courses (OZT) in which $DCPA \leq r$, as shown in Fig. 17, is within an area between the collision courses $Co_{+\alpha}$ and $Co_{-\alpha}$, which are found when $+\alpha$ and $-\alpha$ are given in formula (4).

The collision point is also found so as to identify the most dangerous course. Since the safe passing distance for the course to the collision point is $r = 0$, $\alpha = 0$ is found from formula (3), and $Co_{\alpha=0}$ is calculated by assigning this in formula (4) (the value of $Co_{\alpha=0}$ will be between $Co_{+\alpha}$ and $Co_{-\alpha}$).

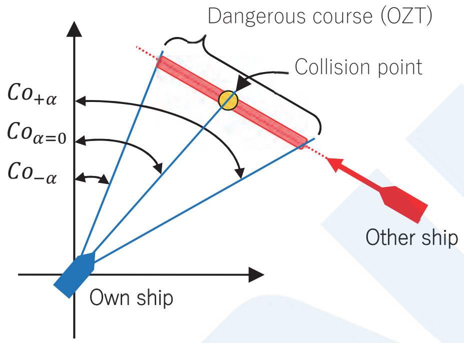


Figure 17　Range of dangerous courses (OZT) and collision point

The master / navigation officer can navigate while securing safe passing distance r to other ship by operating the ship in such a manner that own course does not intersect with the dangerous course defined by the OZT.

While the dangerous course (OZT) is an index in own direction of the ship's course, next, we considered displaying the collision risk area two-dimensionally in the course and distance directions. As shown in Fig. 18, the rhomboidal area with vertexes in the anteroposterior and crosswise directions of the ship is defined as the safe passing area, and the area where other ship enters this area is calculated. The distances to the vertexes (a, b, c and d) can be changed according to the area of navigation.

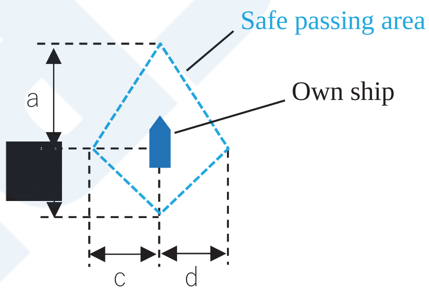


Figure 18　Safe passing area

In calculating the dangerous area, formula (4) is used first to calculate a point on the safe passing area and the point at which the ship collides with other ship, as shown in Fig. 19. Subsequently, this collision point is shifted by a distance corresponding to the safe passing area to the position of the ship. This calculation is performed for all points on the safe passing area. This step is performed repeatedly while changing own course, and only the points in own course direction of the ship are used. Thus, a dangerous area can be calculated.

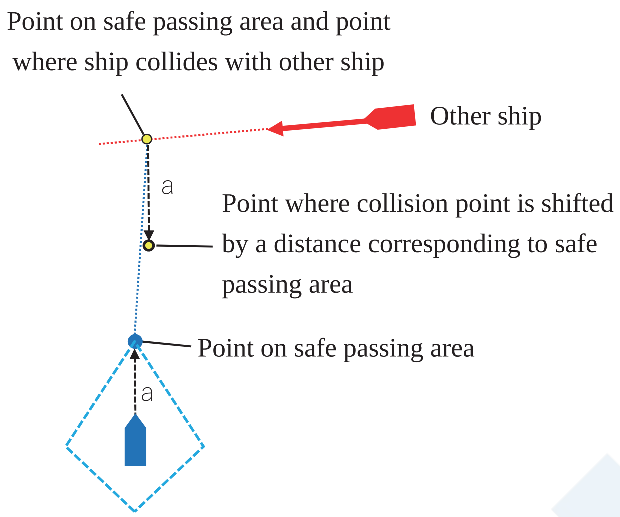


Figure 19　Method of calculating dangerous area

Figure 20 shows an example of a calculation of a dangerous area. This example shows the dangerous area when the speed of the ship is the same as that of the other ship and the course of the target ship is 225°. The master / navigation officer can navigate while securing the safe passing distance shown in Fig. 18 between the own ship and other ship by operating own ship so that it does not enter the dangerous area.

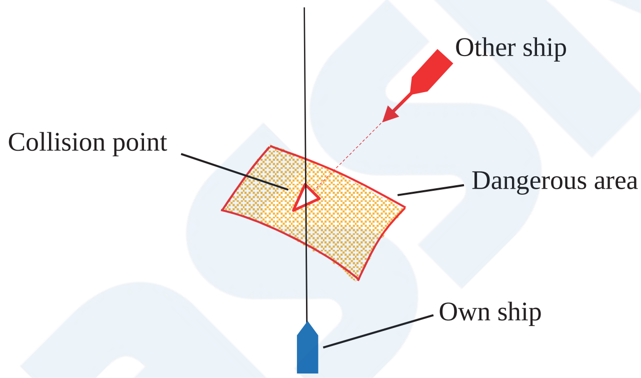


Figure 20　Example of calculation of dangerous area

Figure 21 shows the positions of the own ship and other ship in a situation where the own ship reaches the vertex of the dangerous area. With a dangerous course (OZT), it is only possible to show which course other ship enters the safe passing distance if own ship advances toward the dangerous course. However, with a dangerous area, not only the course, but also the distance that other ship enters the safe passing area becomes clear.

It is thought that dangerous area allows the master / navigation officer to clearly recognize the area where the ship can safety navigate. As an additional advantage, since the dangerous area represents the area that should be avoided as a plane, the route on which the ship can navigate can be seen more clearly than in the case of the dangerous course.

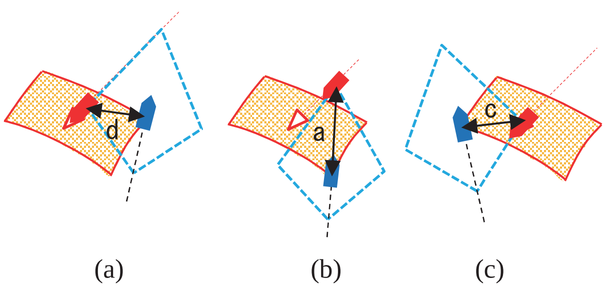


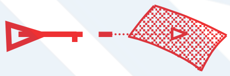
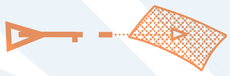
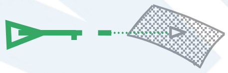
Figure 21　Distance to other ship at vertex of dangerous area

To summarize the foregoing discussion, the meanings of the dangerous course (OZT), the dangerous area and the collision point are as follows.

[Dangerous course]
If own ship advances in the indicated direction, other ship will enter the safe passing distance.
[Dangerous area]
If own ship enters the indicated area, other ship enters the safe passing distance.
[Collision point]
If own ship advances in the indicated direction, it will collide with other ship.

Table 4 shows the method for displaying a dangerous course (OZT) and a dangerous area. The colors are changed according to the results of the risk level judgment using the collision risk index.

Table 4　Method for displaying dangerous course/dangerous area

Risk level	Color	Dangerous course	Dangerous area
Danger	Red		
Warning	Orange		
Safe	Gray		

In the display of a dangerous course, the shape is an arrow and course of other ship is indicated with the direction of an arrow. By contrast, in the display of a dangerous area, it is difficult to express the direction by the shape of the area itself. Therefore, the shape of the collision point is expressed by a triangle, and the course of other ship is indicated by the direction of this triangle.

Figure 22 shows an example of a dangerous course displayed on the actual radar screen, while Fig. 23 shows an example of a dangerous area displayed on the screen. The two figures show the same situation, and the dangerous course shown in Fig. 22 is expanded to a two-dimensional area in Fig. 23. This enables the master / navigation officer not only to confirm the course, but also to recognize how far other ship will enter the safe passing area.

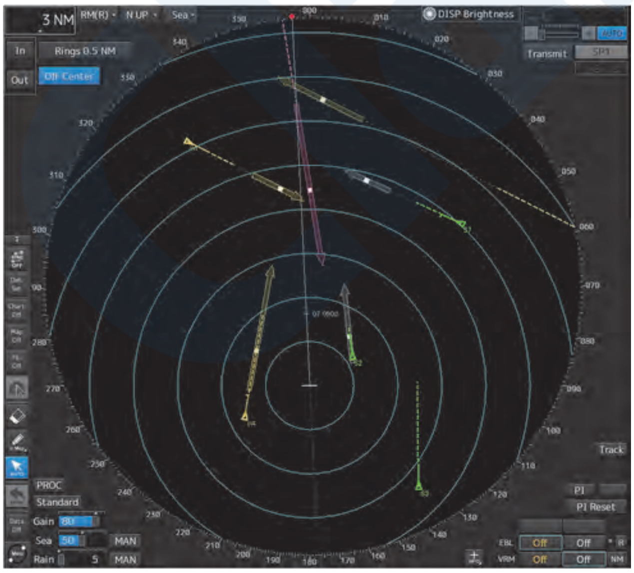


Figure 22　Example of dangerous course display

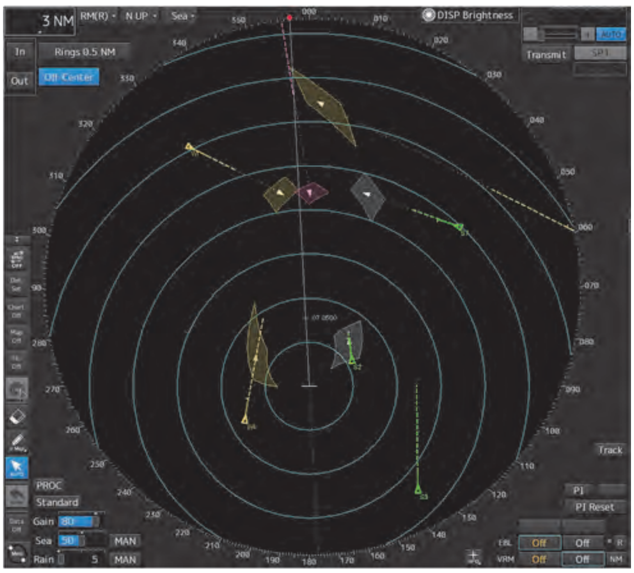


Figure 23　Example of dangerous area display

As with the collision risk index, a prototype for displaying the collision risk area was incorporated in the radar, and a ship operation simulation test was conducted to confirm its effect. The test was conducted for a dangerous course and a dangerous area using the same scenario. It was found that the display is highly effective, as the frequency of collisions with other ships was much smaller than without the display. Although there was not a large difference between the dangerous course and the dangerous area, many master / navigation officers reported that it was easier to find a collision avoidance route with the dangerous area display. However, some operators commented that the dangerous areas overlapped in cases where many ships were present, resulting in a complicated display that was difficult to see.

We will also study practical application of the collision risk area display in the future. Since this function, like the collision risk index, is intended to prevent collisions, it is considered most appropriate to incorporate the function in the radar. Unlike the collision risk index, the display of a collision risk area is not a function which is required by rules. Therefore, incorporation of this function in the radar as an additional function for practical use is considered possible. Moreover, because this function will also be effective for ECDIS, which plays an important role in determining the ship's route, it is necessary to consider incorporating the function in the ECDIS system. In addition, this function is also considered to be an essential technology for providing collision avoidance routes in collision avoidance support devices intended for automatic navigation.

3.3 Technological Development by Tokyo Keiki Inc.

3.3.1 Collision Risk Index

Referring to the existing indexes, Tokyo Keiki developed "normalized CPA risk" as a collision risk index based on DCPA/TCPA in which DCPA and TCPA are each normalized with a weighting factor W. (Note: The indexes are divided by W, and the value range is converted to 0 to 1.) The results are then subtracted from 1 and multiplied together to obtain a risk level in a range of 0 to 1 (see Fig. 24). If the original value is larger than W, the normalized value is regarded as 1.

This index is intended to be closer to the sense of master / navigation officers by varying the weighting factor according to the encounter situation, while keeping a simple composition based on CPA information, which is familiar to master / navigation officers.

$$\text{Normalized CPA Risk} = \left(1-\underbrace{\frac{\mathbf{DCPA}}{\mathbf{W_{dcpa}}}}_{\text{Normalized DCPA}}\right) * \left(1-\underbrace{\frac{\mathbf{TCPA}}{\mathbf{W_{tcpa}}}}_{\text{Normalized TCPA}}\right)$$

DCPA : Distance of CPA , W_{dcpa} : weighting factor (>0)
TCPA : Time to CPA , W_{tcpa} : weighting factor (>0)

Figure 24　Calculation formula for normalized CPA risk

The weighting factors of DCPA/TCPA are explained below. The weighting factor of DCPA (W_{dcpa}) is set on the basis of a circular safe passing area that is assumed to exist around the ship. The weighting factor of TCPA (W_{tcpa}) is varied according to the angle of encounter with another ship, which can be considered to be a characteristic feature of this index. In concrete terms, when a ship is in a situation of possible collision with another ship, the TCPA at the time when "the course change angle for safely avoiding the other ship by securing a certain distance regardless of the encounter situation is the same (in other words, the range of the dangerous courses is the same)" is calculated for each encounter situations, and W_{tcpa} is set based on a graph connecting the results (see Fig. 25).

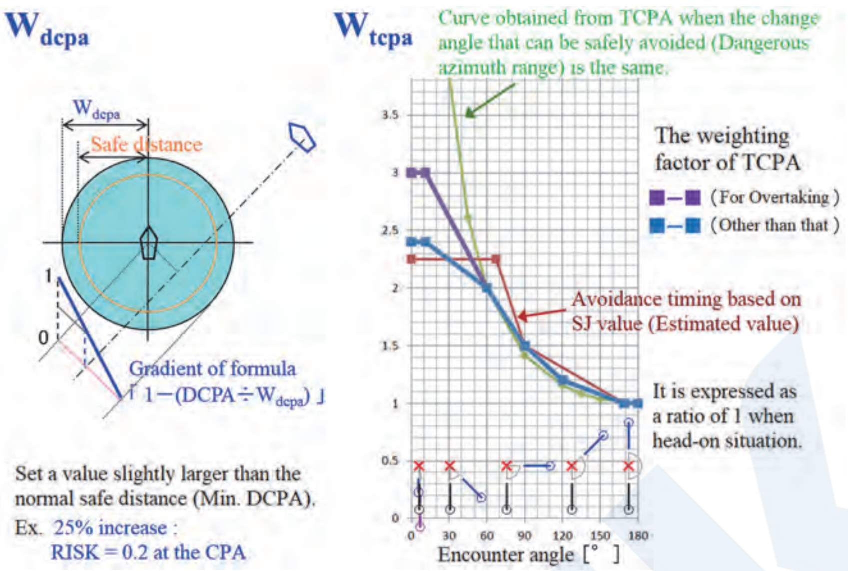


Figure 25　Weighting factors for normalized CPA risk

Looking at the range of dangerous courses (i.e., the course change angle for collision avoidance) when the normalized CPA risk set using the weighting factors as described above had almost the same value in encounter situations with the same DCPA and different TCPA, the value was almost the same regardless of the encounter situation, as was expected (see Fig. 26).

On the right side of the figure shown below, the range of dangerous courses is expressed by using DAC, which is described later. The graph at the lower left represents a “normalized CPA coordinate system,” in which the normalized DCPA values and normalized TCPA values are plotted on the abscissa and the ordinate, respectively, and the multiple curves in the coordinate system are the “risk level curves” that are obtained by modifying the normalized CPA risk formula. In this coordinate system, the upper right part represents a safe state, and the lower left part is a dangerous state. Therefore, if the normalized values for each of the other ships are plotted, application of this index to prioritization of actions when responding to other ships can be expected.

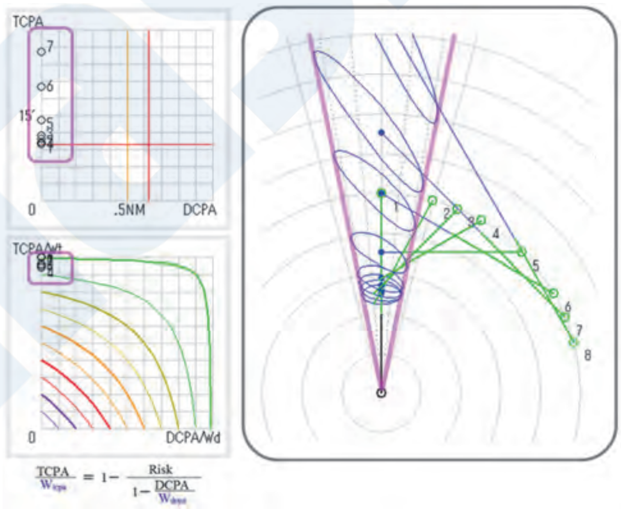


Figure 26　Example in which normalized CPA risk substantially coincides with range of dangerous courses

Comparing the set W_{tcpa} graph and the TCPA at the time of collision avoidance based on the SJ value (subjective judgment of collision risk level) corresponding to the angle of encounter, the two show very similar trends (see the graph at the right in Fig. 25). Therefore, the W_{tcpa} setting method described above is considered to fulfill the purpose of creating this index, which is “to be closer to the sense of master / navigation officers.”

Validation and study for further improvement of the normalized CPA risk index are currently in progress. In the future, the company aims to achieve the following uses of the index by incorporating normalized CPA risk in radar, ECDIS/ECS, *etc.*

- Risk level display (numerical value, time series graph)
- Color coding of attributes for display of other ships according to the risk level
- Issuance of alarms according to the risk level
- Identification of the status of other ships based on the normalized CPA coordinate system
- Application to the risk level in the collision avoidance algorithm

A patent application for normalized CPA risk has already been submitted.

3.3.2 Collision Risk Area

Since the 1970s, Tokyo Keiki has provided functions for displaying “collision areas” such as PAD (Predicted Area of Danger) and DAC (Dangerous Area of Collision) in radar, as shown in Fig. 27.

Figure 27 Tokyo Keiki products incorporating “collision area” display functions

In PAD, as shown in Fig. 28, a range of dangerous courses when another ship approaches the ship inside the safe passing distance that should be secured is set on the true course of the other ship, and the depth perpendicular to the other ship’s course is expressed by an ellipse or a hexagon, which is assumed to represent the safe passing distance.

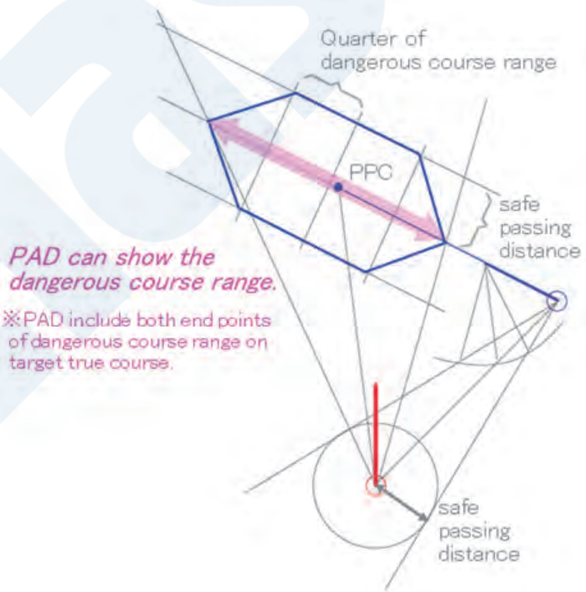


Figure 28 Principle of PAD (case of hexagonal PAD)

In contrast, as shown in Fig. 29, DAC accurately displays the danger area where another ship approaches the ship inside the safe passing distance by calculating the vertexes of the “safe passing area,” which approximates a circle with its radius representing the safe passing distance as a polygon (① to ⑧ in the figure), and the point of collision with the other ship, using the ship's positions when the vertexes collide (①' to ⑧' in the figure) as component points.

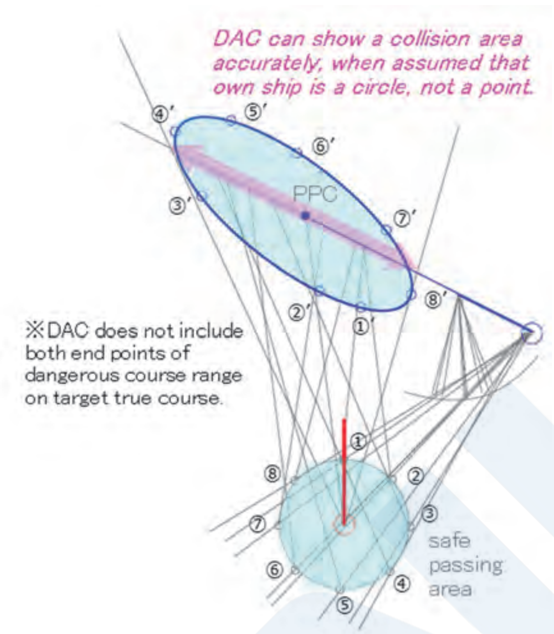


Figure 29　Principle of DAC (case of octagonal DAC)

It is not easy to accurately find a collision avoidance course change angle at which a safe passing distance can be secured from information based on the conventional closest point of approach method, even in simple encounter situations. For example, in Fig. 30 (left), the display shows that the ship passes the stern of a ship passing in front of it by steering to the right, but the course change required to secure the necessary passing distance is not immediately apparent. However, since a "collision area" such as DAC can accurately indicate the range of dangerous courses, the master / navigation officer can determine the necessary course change on the screen, as shown Fig. 30 (right). [4)]

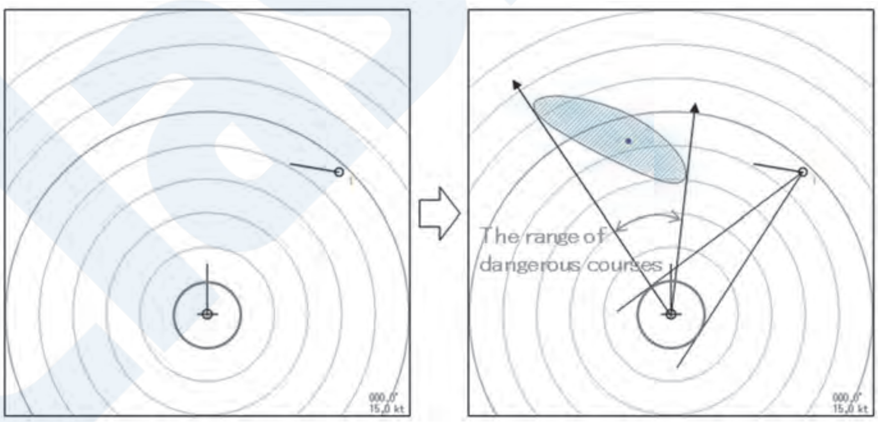


Figure 30　Identification of the range of dangerous courses in DAC display

Furthermore, DAC not only enables the master / navigation officer to confirm the range of dangerous courses in the same manner as with PAD, but can also accurately display the depth direction (direction perpendicular to the direction of the true motion of another ship). Therefore, even if another ship enters the safe passing area, DAC can continue to display the ship and estimate the following:

① How soon the other ship will enter the area
② How long the other ship will travel in the area
③ When the other ship will leave the safe passing area

In Fig. 31, the numbers ① to ③ and ①' to ③' represent the ranges of the above items and the range corresponding to numbers ① to ③ on the relative motion line, respectively.

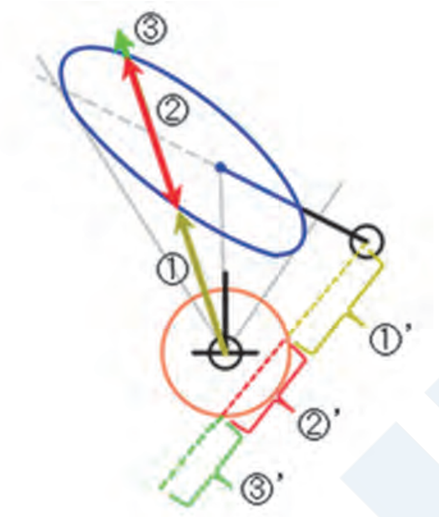
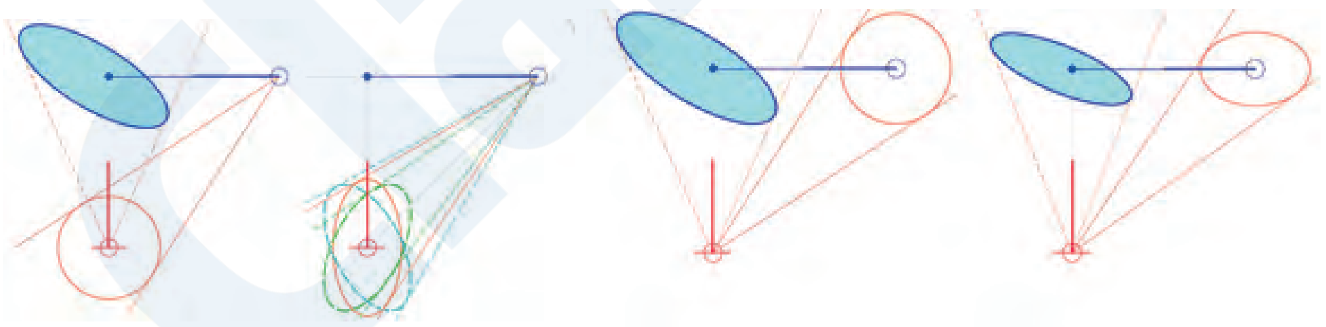


Figure 31　Depth information of DAC

In the conventional DAC, a safe passing area was set as a perfect circular shape around the ship (Fig. 32 (a)), but according to findings of marine traffic engineering, the actual shape of such a passing area should be an ellipse which is elongated in the travel direction and narrower in the lateral direction. However, if an elliptic area was set around own ship with the conventional DAC, the range of dangerous courses will change depending on the direction of own ship, and as a result, DAC will lose its key features of "safety without trial ship operation/possible to understand dangerous courses at a glance." Therefore, this setting was not realized (Fig. 32 (b)).

To solve this problem, a new method for setting the safe passing area around another ship was devised. If the shape is a perfect circle, the displayed shape, size and position of the DAC are the same as those of the area set around own ship (Fig. 32 (c)). Further, if the shape is elliptic, the problem that the range of dangerous courses changes depending on the direction of own ship does not occur (Fig. 32 (d)). It also became possible to shift the center of the area from the position of another ship (offset). A Japanese patent has already been granted for this new DAC method, and foreign patents are pending.



(a)　(b)　(c)　(d)

Figure 32　Change of placement of safe passing area with DAC

In the existing product shown in Fig. 27, PAD and DAC were line drawings due to the limitation of computer drawing processing capability. However, recent PCs have significantly improved drawing capabilities and are capable of displaying the "collision area" more graphically. Figures 33 and 34 show the comparison of a line drawing and a 2D drawing of DAC. Thus, a new display method which improves the visibility of DAC is under development, and implementation in devices such as radar and ECDIS is planned in the future.

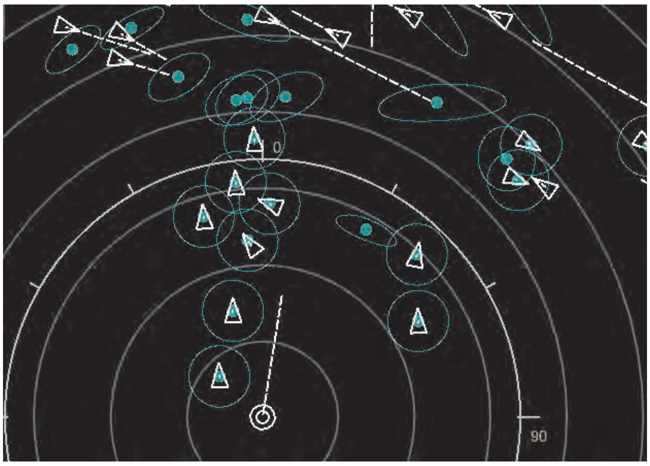


Figure 33　Example of DAC display (line drawing)

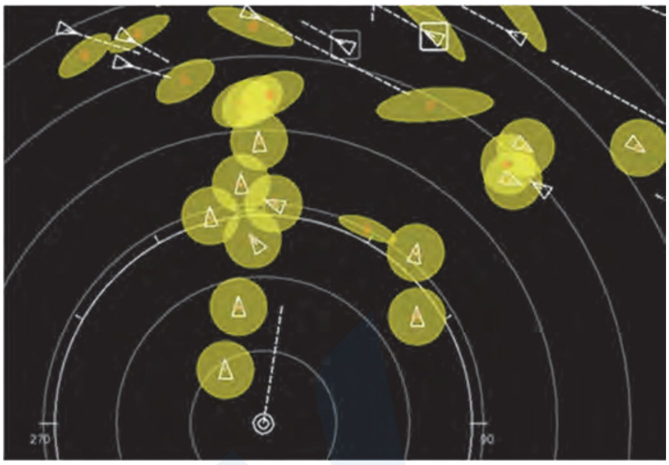


Figure 34　Example of DAC display (transparent fill)

Recently, navigation support information has also become available via the internet using mobile devices such as smartphones and tablet terminals. “Aisea” (https://aisea.net/), which is operated by Aidea Inc., is an example of this type of system. In cooperation with Aidea Inc., Tokyo Keiki developed a new version of DAC with the aim of incorporating a DAC display function into “Aisea PRO,” which is a corporate-type application platform, and an updated version of DAC including this function was released in August 2020. Figure 35 shows an example of a DAC display on the “Aisea PRO” screen.

“Aisea PRO” is capable of displaying areas with a risk of collision with other ships in red, yellow and blue in the order of risk levels. The aims of this function are to reduce the burden on the master / navigation officer and realize support for decision-making in ship operation for collision avoidance.

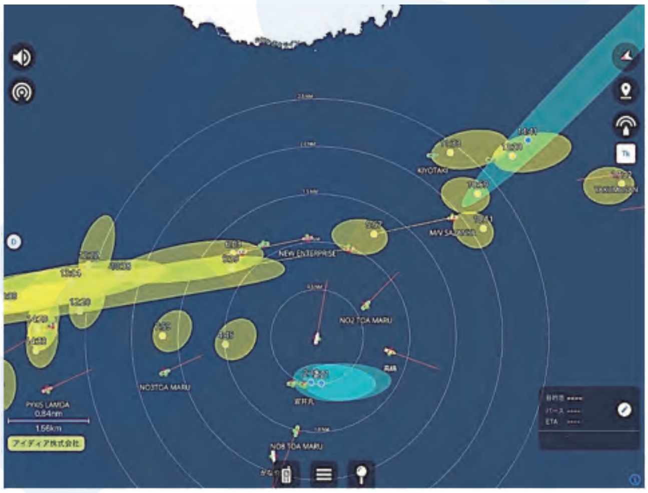


Figure 35　Example of DAC display on “Aisea PRO”

Tokyo Keiki also concluded a business intermediary contract and service outsourcing contract with Aidea Inc. for sales of “Aisea PRO” and started this business in January 2021. Tokyo Keiki will work to contribute to safer navigation and higher efficiency in operation management by promoting wide adoption of “Aisea PRO.”

4.　VERIFICATION OF EFFECT OF COLLISION RISK INDEXES AND COLLISION RISK AREAS

A ship handling experiment using a ship handling simulator was conducted in order to objectively and quantitatively evaluate the effectiveness of the collision risk indexes (alarms by colors or sounds) developed by Furuno Electric, Japan Radio and Tokyo Keiki based on data on the sense of risk of experienced master / navigation officers collected in this study, and the collision risk area display, which visualizes the basis for the risk indexes. This section presents an outline of the ship handling experiment and details of the results of a quantitative evaluation of the findings from ship handling operation by using the track charts and a ship handling evaluation program.

4.1 Simulator Experiment

4.1.1 Outline of Experiment

Using a scenario that assumed congested waters, a comparative evaluation was conducted for a case where the subjects performed normal ship handling based on information collected by radar (without support) and a case where the subjects performed ship handling using a ship operation support device that displayed collision risk indexes/areas under the same scenario (with support). As the comparative verification method, the track charts were compared, and a ship handling evaluation program owned by Japan Marine Science was used.

This experiment was conducted during a period from 2019 to 2020 with subjects having varied levels of experience, ranging from captains with extensive experience in operating ocean-going ships to junior navigation officers and cadets (students belonging to maritime education institutes). This subsection introduces the result of an experiment with cadets that was conducted in 2020 using an established evaluation method. As an example of the results of a typical experiment, the following introduces the results of an experiment using a ship operation support device created by Furuno Electric.

4.1.2 Experimental Scenario

The scenario used in the evaluation of the experiment assumed a large containership operating in the congested waters around Singapore, in which the ship enters the sea lane while the master / navigation officer observes the situation of passing ships. The outline of the ship and the scenario chart are presented below. (In Fig. 36, the red track represents the ship's track regarded as ideal.)

Table 5 Outline of ship used in experiment

Outline of ship used in experiment	
Ship type	Containership (9100 TEU)
Ship model (L/B/d)	349.8 m/45.6 m/14.5 m
Set speed	12 kt (S/B Full)

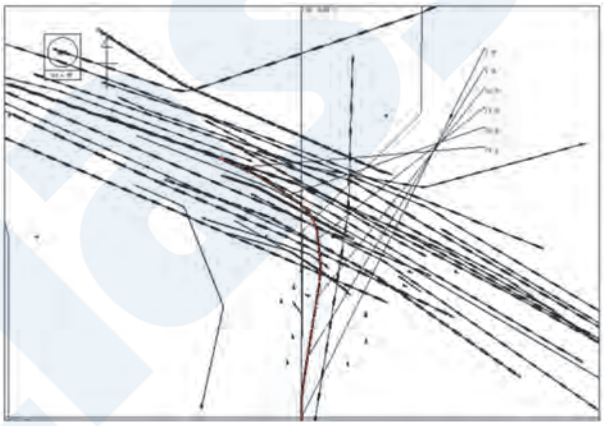


Figure 36 Outline of scenario used in experiment

As the precondition for this experiment, the speed (engine power) of the ship was set to a constant condition and ship operation for collision avoidance was performed using only the rudder so that changes in the encounter situation resulting from changes in the speed of the ship would not affect the comparative verification.

4.1.3 Evaluation Method

As the method for objectively and quantitatively evaluating the effectiveness of the collision risk indexes/area display, track charts and a ship handling evaluation program were used.

In the evaluation using the track charts, a comparative verification was conducted by overlapping the tracks of multiple ships on a gridded sheet and analyzing the variations in the tracks. The size of the adopted grid was 500 meters square, which was based on the results of interviews with master / navigation officers, who reported that the passing distance with another ship that the master / navigation officer should secure in congested waters is approximately 2.5 to 3 cables (approx. 500 m).

In the evaluation using the ship handling evaluation program, the “Auto Grading System” (hereinafter abbreviated “AGS”) owned by Japan Marine Science was adopted. AGS is software which is provided with a ship handling simulator made by Japan Marine Science and is capable of expressing ship handling results by scores based on a quantitative evaluation of the results of various evaluation items, such as encounter situations with other ships, buoys, rocks and other marine obstacles and no-go areas (NGA).

The basic evaluation formula for the ship handling results with AGS is intended to produce a result based on non-dimensional negative scores by dividing the dangerous area entry time for each evaluation item by the ship operation time.

$$Score = -\frac{x * t_{Dangerous} + y * t_{Caution}}{t_{end}} *$$

where,

Score: Evaluation score

$t_{Dangerous}$: Period/time in Dangerous area (s)

$t_{Caution}$: Period/time in Caution area (s)

x: Variable for Dangerous area for weighting

y: Variable for Caution area for weighting

t_{End}: Period/time of ship maneuvering (s)

A result in which a ship operation accident occurs (called a “Consequence” in this system) and the degrees of violations of safety constraints such as entering a NGA in the process leading to that result were arranged hierarchically, as shown in Fig. 37, and weights were assigned to each item.

Figure 37 Degrees of violations of safety constraints

AGS is intended to evaluate any ship handling action that may lead to a ship operation accident. Therefore, for “Consequence,” which is the top-ranked degree of violation in Fig. 37, the system detects and displays the event but does not evaluate it. Accordingly, the evaluation items are the levels “Approaching to Safety Constraint” and “Process to Approaching Safety Constraint.” Table 6 shows the result of classifying the evaluation items as described above. The weighting factors (Wf) for the two levels below “Safety Constraint” are 2 for the higher level items and 1 for the lower.

Table 6 AGS evaluation items and weighting factors (Wf)

Id	Layer	Items	Wf.
1	Consequence (accident)	Collision	n/a
2		Grounding	n/a
3	Approaching to Safety Constraint (To Object)	Relationship with other ship (distance and heading change rate)	2
4		Relationship with other ship (e.g., fishing boat)	2
5		Buoy passing distance	2

6		Passing distance of an arbitrary point	2
7		Deceleration in docking	2
8	Approaching to Safety Constraint (To Area)	NGA entry	2
9		Navigation outside designated course	2
10	Process to Approaching Safety Constraint	ROT limit	1
11		Speed limit in course	1
12	Other (Economy)	Economic operation index	n/a

This evaluation program contains an evaluation formula [5)] based on a "Dangerous area chart" in evaluations of the relationship with other ships. The method uses the relative distance and the rate of bearing change when another ship passes as indexes, and is capable of evaluating when another ship passes with a very fine mesh of 1 s. Its validity has been established based on a background of many years of research.

4.2 Results of Experiment

4.2.1 Evaluation and Analysis Using Track Charts

Figure 38 shows the results of ship handling by 15 subjects in the form of track charts. The track chart at the left is the result of normal ship handling (without support), and that at the right is the result of ship handling under the same scenario using a ship operation support device (with support). The blue tracks are "tracks of navigation without collision," and the red tracks are "tracks with collision" or "tracks of reverse navigation on the course."

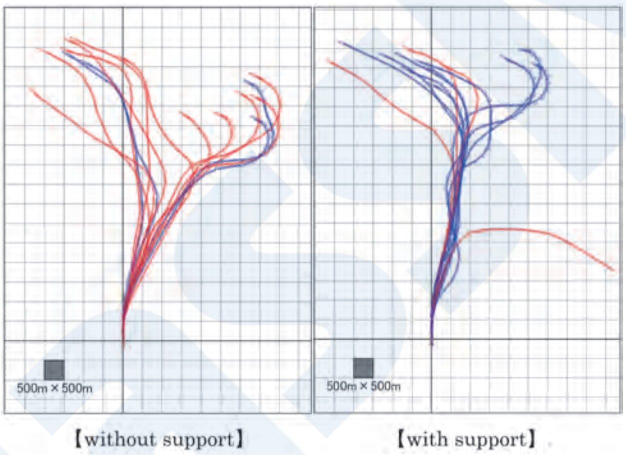


Figure 38 Track charts showing ship handling results

In this verification, 11 collisions occurred during 15 rounds of the test "Without support," but in the test "With support," the number of collisions decreased to 4. This is attributed to the fact that the support displays allowed the master / navigation officer to notice other ships with a high collision risk at the proper time and easily determine an appropriate collision avoidance action by visually recognizing waters with a high collision risk. This can be interpreted as suggesting that the result of complementing the differences in the individual situational awareness abilities and experience of the subjects is expressed in the convergence of the ship tracks.

It may also be noted that the results of an experiment under the same scenario in FY 2019, in which the subjects were license holders (professional captains and navigation officers), also showed better convergence of the tracks in the test "With support" than in the test "Without support," and the number of collisions was reduced to only 0 or 1 in the test "With support."

4.2.2 Evaluation and Analysis Using Auto Grading System

Table 7 shows the results of the comparative verification using the AGS ship handling evaluation program. The comparison was conducted for tests "Without support" and "With support." The results are shown by the colored arrows in the table. Although collisions occurred in the experiment, as described above, the score is not reduced for the respective items in AGS, but the fact that collisions occurred is shown together with evaluation for the other items. For this reason, results containing a collision were excluded from the score-based comparison. Entry into the oncoming lane (reverse travel) also occurred in some cases. For entry into a NGA, points are deducted to some extent in this case. However, in this experimental method, entry into the oncoming lane results in an extreme decrease in encounters with other ships, which would affect the scoring of the passage of the other ships. Therefore, as with collisions, results containing reverse travel were excluded from the score-based comparison.

Table 7　Evaluation of results of ship handling by auto grading system

Subject (cadet)	Result of evaluation by AGS		
	Without support (radar only)	With support (collision risk display)	Comparison
A	Collision	-109.29	↑
B	Collision	-111.84	↑
C	Collision	Collision	→
D	Collision	-129.83	↑
E	-107.43	-66.43	↑
F	Reverse travel	Collision	→
G	Collision	-63.96	↑
H	-67.07	-84.22	↓
I	Collision	Reverse travel	→
J	-119.10	-61.83	↑
K	Collision	-51.13	↑
L	Collision	-55.30	↑
M	Collision	-113.89	↑
N	Collision	-29.21	↑
O	-146.11	Reverse travel	↓
Average (*)	-109.9	-87.7	↑

<Legend>

↑ In comparison to the test “Without support,” the score increased or no collision/reverse travel occurred in the test “With support.”

↓ In comparison to the test “Without support,” the score decreased or collision/reverse travel occurred in the test “With support.”

→ Collision/reverse travel occurred in both the test “Without support” and the test “With support.”

* The average score is the value obtained by dividing the total score calculated without collision/reverse travel by the number of subjects.

Based on Table 7, the results of an evaluation of 10 of the 15 subjects showed that more appropriate shiphandling” was generally performed in the test “With support” than in the test “Without support.” From the above-mentioned track charts, it is clear that the number of collision decreased in the test “With support,” and the average score calculated using the auto grading system was also higher in the test “With support” than “Without support.” Thus, a certain ship operation improvement effect was observed with the use of the ship operation support device.

4.3　Discussion

Based on the findings of this study, the effects of the collision risk indexes and area display and the importance of education in utilizing this ship operation support device are summarized as follows.

4.3.1　Effects of Collision Risk Indexes/Area Display

The results of the simulator-based experiment and verification proved that issuance of warnings based on a collision risk index enables early discovery of collision risks by the master / navigation officer, and visualization of the basis for judging that a situation is dangerous as an area display contributes to levelling the variations in the skills of individual masters /

navigation officers, reduced collision risk and improved safety. In particular, it is suggested that the indexes/area display are highly effective in transverse passing situations, as shown in the scenarios examined in this section. In cases where a ship passes transversely across a line of multiple ships with different speeds travelling in succession, for example, when passing a sea lane, the master / navigation officer must predict the movement of each ship and the arrangement of the group of ships in the future, i.e., the future relative relationship of the ships, and then analyze and decide the route that the own ship should take. It can be said that the device described here facilitates this task. This was clearly demonstrated by the fact that a large number of collisions occurred in the test “Without support,” while the number of collisions was reduced to nearly zero in the test “With support.”

The following secondary effects can also be expected as a result of reducing the workload on the ship’s crew.

- Reduction of judgment errors by alleviating psychological stress.
- Reduction of judgment errors by allowing more time for thinking.
- Reduction of cases of overlooking important targets by observing the surroundings more calmly.
- Improvement of judgment in situations where visual confirmation is difficult, for example, at night or under low visibility conditions.

Future tasks will include preparation for system implementation in order to ensure system operation oriented toward the safety and security of the master / navigation officer by adjusting the ship operation support device for various users and ship operation environments and constructing a man-machine interface with high usability, while also focusing on the above-mentioned secondary effects.

4.3.2 Education for Utilizing Ship Operation Support Device

The effects of the collision risk display described in the preceding section are clear. However, the possibility that use of a new ship operation support device may compromise safety, depending on how well the user understands the device, was pointed out as a problem in the experiments conducted to date. Education was recently given to mates and cadets, and as a result, several perspectives were obtained, as summarized below.

- Deepening the understanding of the ship operation support device by education can contribute to the improvement of safety.
- Even if the same education is provided, the degree of understanding will vary depending the person. Therefore, it is essential to give education and training according to the levels of individuals, for example by specifically clarifying matters that seem to be inadequately understood, through workshops or the like, and providing additional individual education.
- Effective use of the ship operation support device requires knowledge/experience in ship operation practices, which are prerequisites for effectively using the device. Therefore, operation, including education and training, should be studied after clarifying the knowledge and skills required in master / navigation officers.

From the above, assuming the target of education is masters / navigation officers with varied levels of experience and skill, education for masters / navigation officers is considered to be an essential requirement. The future aims are proving the necessity of these forms of education by providing more convincing data, and establishing educational requirements for safe operation of the device.

5. SUMMARY

5.1 Results of Study

Concerning the collision risk indexes developed in this study, the companies concerned established collision risk notification algorithms based on the data from tests conducted with active ocean-going captains and navigation officers and developed prototype systems. Using a combination of the collision risk indexes and the collision risk area display, the master / navigation officer can be made aware of risk by issuing collision risk indexes, and can recognize ships with a risk of collision at an earlier timing than with the conventional visual and radar-based ship operation and select a safe course quickly, based on information concerning waters with a high collision risk provided by the collision area display. In the ship handling experiment using a ship handling simulator conducted with experienced masters / navigation officers, the number of collision accidents was significantly reduced when the prototype device was used in comparison with operation without the device, and when students with little experience in ship handling used the device, a sufficient effect was observed after education on the use of the device.

However, some masters / navigation officers failed to fully understand the functions of this device or to make full use of it. Although the number of such cases was small, as a future task, it will be necessary to study education to ensure full use of the collision avoidance support device.

5.2 Future Efforts

The navigation device manufacturers have completed prototypes of the functions and devices developed in this study. In the future, each company will pursue improvement and verification with the aim of commercializing the developed functions and devices.

The aim of the manufacturers is to achieve commercialization by around 2025 after conducting repeated verifications, bearing in mind the need to obtain approval for the devices from ship classification societies and other authorities. After the verifications are conducted, the marine transportation industry should work to substantially reduce collision accidents, prevent environmental destruction caused by accidents and improve customer services by installing the developed functions and devices on ships. In addition, Japan Marine Science intends to develop a more advanced version of the auto grading index developed in this study in order to evaluate autonomous ship operation systems that will become available in the future, and to pursue proposals to concerned parties inside and outside of Japan concerning evaluation methods for autonomous ship operation systems, which are expected to be standardized in the future.

6. CONCLUSION

As described in this paper, the contribution of the collision risk judgment method developed in this study to improving safety by levelling variations in the skills of individual masters/ navigation officers and reducing collision risk has been amply demonstrated. In the final fiscal year of the study, an experiment was conducted with candidates for navigation officer who had not yet received licenses, and it was found that the system is also effective in improving the safety of ship operation by relative inexperienced navigation officers to a certain extent, proving that the system can be adapted to various users.

In the future, this effort will proceed from the research and development stage to the implementation and practical use stage. The research findings from this study can be used not only for safety improvement through ship handling support for masters/ navigation officers of existing ships, but also as a basic technology for the situation assessment function in the automated operation ships which are currently under development.

Furthermore, this research and development project has also helped to revitalize the maritime industry, as the participants grappled with problem-solving suited to current conditions in order to prevent collision accidents by combining the knowledge of manufacturers and front-line personnel through joint efforts by navigational device manufacturers and the marine transportation industry, and businesses in the same industry worked jointly on the development with an awareness of the appropriate regions for cooperation and competition.

Currently, the members of this study team are participating in a “Demonstration project for ships using a ship operation support function and remote ship operation, *etc*.” conducted by Japan’s Ministry of Land, Infrastructure, Transport and Tourism, and a DFFAS project in a “Joint program for technological development related to a demonstration experiment of an unmanned operating ship” (MEGURI 2040) of the Nippon Foundation, in order to achieve safe navigation, including reduction of collision accidents, and improve the working environment for crew.

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ABBREVIATIONS

ICT: Information and Communication Technology
IoT: Internet of Things
CPA: Closest Point of Approach
DCPA: Distance of CPA
TCPA: Time to CPA
ARPA: Automatic Radar Plotting Aid
PAD: Predicted Area of Danger
DAC: Dangerous Area of Collision
OZT: Obstacle Zone by Target
AIS: Automatic Identification System
IMO: International Maritime Organization
ECDIS: Electronic Chart Display and Information System
ECS: Electronic Chart System
SJ: Subjective Judgment
AGS: Auto Grading System
NGA: No Go Area