

Development of Automatic Collision Avoidance System and Quantitative Evaluation of the Manoeuvring Results

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ABSTRACT: The automatic collision avoidance system introduced in this paper is a system constantly calculating optimal manoeuvring method from the risk and economic preference in the ship manoeuvring space where the course change and the deceleration are performed. The authors also propose a system that quantitatively evaluates the collision avoidance manoeuvring results. Based on the evaluation results of this system, the authors are setting parameters so that ship manoeuvring that does not give anxiety to target ships to be avoided is also realized in automatic collision avoidance manoeuvring. In addition, comparison between the manoeuvring results of the automatic collision avoidance system and the veteran captain's manoeuvring results was quantitatively compared by the proposed evaluation system. Verification experiments were successfully conducted to verify the effectiveness of the proposed automatic collision avoidance system on the actual ship navigating in congested waters.

1 INTRODUCTION

About 80% of ship collision is reported to be caused by human error. And most of this human error is "lack of situational awareness". One of the methods to prevent the collision caused by the "lack of situational awareness" is the adoption of a system that constantly grasps the level of collision risk with vessels encountered and assists in selecting the optimal method of collision avoidance manoeuvring. Therefore, the authors developed an automatic collision avoidance system that helps prevent human error. Several researches have been done on automatic collision avoidance system [1],[4],[5]. The system developed by the authors is a system constantly calculating optimal manoeuvring method from the risk and economic preference in the ship manoeuvring space where the course change and the deceleration are performed. The system basically takes actions according to the International

Regulations on the preventing collision at the sea (COLREGs) and also considers the manoeuvrability of the ship. In order to verify the effectiveness of this system, many verification experiments were conducted using a full mission simulator. And experiments were also successfully conducted to verify the effectiveness of the proposed automatic collision avoidance system on the actual ship navigating in congested waters. It was verified by this verification experiment on an actual ship that it was a practical level as a collision avoidance support system. This system is not limited to the collision avoidance support system, and in the future, it is one of the extremely effective elemental technologies as an automatic collision avoidance system to be installed on unmanned autonomous ship.

In addition, the authors proposed a method to quantitatively evaluate the collision avoidance manoeuvring results. Using this evaluation method,

we have compared the results of the automatic collision avoidance system with the results of ship manoeuvres by humans, and based on these evaluation results, we confirmed that the automatic collision avoidance system performs manoeuvres equal to or better than veteran captains.

Furthermore, the authors point out that it is important to conduct manoeuvring in which the manoeuvring by the automatic collision avoidance system does not give anxiety to other ships in the sea area where the ships manoeuvred by humans and ships manoeuvred by the automatic collision avoidance system coexist. The developed automatic collision avoidance system objectively verified that it did not give anxiety to other ships.

2 CONCEPT OF AUTOMATIC COLLISION AVOIDANCE MANOEUVRING

2.1 Strategic Collision Avoidance Manoeuvring

The authors developed an automatic collision avoidance system considering the realization of strategic collision avoidance manoeuvring. Strategic collision avoidance manoeuvring means ship manoeuvring which minimizes the economic loss, constantly selects a low-risk course from an early stage and reduces the encounter situation where the manoeuvring load is high. General ship navigator selects avoidance manoeuvring method in consideration of avoiding the risk of collision and minimizing economic loss. However, there are individual differences in the collision avoidance method. The method of collision avoidance manoeuvring is not uniform, such as a method of choosing to alter her course drastically after the risk of collision becomes prominent, or a method of slightly altering her course before rules defined by COLREGS is applied. The automatic collision avoidance system for realizing the strategic collision avoidance manoeuvring proposed by the authors is based on the latter manoeuvring.

2.2 Calculation of Collision Risk and Preference in the Collision Avoidance Manoeuvring Space[3]

When a navigator decides the method to prevent a collision, two principal requisites should be considered. One is the risk of collision and other is the economic loss of voyage. These two factors conflict with each other and have a different dimension, however both factors can be assessed on the same plane by using the collision avoidance manoeuvring space concept. Figure 1 shows the collision avoidance manoeuvring space model ($X_{i,j}$). The horizontal axis is a course (i), the longitudinal axis is a speed (j) and the evaluation value of each manoeuvre ($Pb(X_{i,j})$) is extended perpendicularly upward. In the collision avoidance manoeuvring space, the evaluation value for each ship manoeuvring method is calculated from the collision risk and the economic preference. The shape of a figure like a roof in the Figure 1 shows one model of preference order as expressing a general tendency with exponential function. The model of preference order is expressed as follows;

$$\begin{aligned} Pb(X_{i,0}) &= \exp(-a_c \cdot \Delta Co) \\ Pb(X_{0,j}) &= \exp(-a_v \cdot \Delta V) \\ Pb(X_{i,j}) &= Pb(X_{i,0}) \cdot Pb(X_{0,j}) \end{aligned} \quad (1)$$

where, $Pb(X_{i,j})$ is evaluation value of preference of manoeuvre $X_{i,j}$, ΔCo is degree of altering course, ΔV is ratio of reduction speed, a_c and a_v are the coefficient to calculate the preference order. In this figure, the evaluation value is highest for maintaining the present course and the present speed. Altering the course to the starboard is higher than altering the course to the port. According to this preference model, as a method of avoidance manoeuvre, first, altering the course to the starboard is given priority at the present speed.

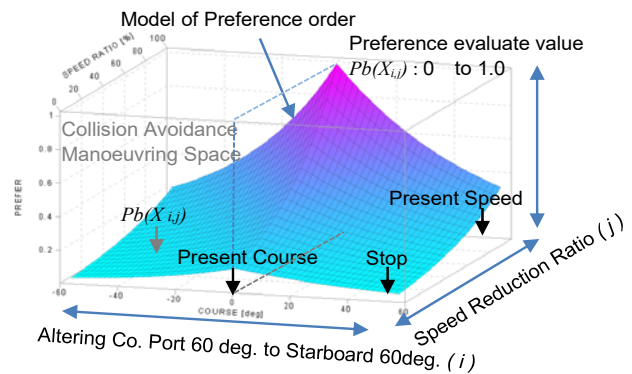


Figure 1. The collision avoidance manoeuvring space, and one model of preference order as expressing a general tendency: $Pb(X_{i,j})$

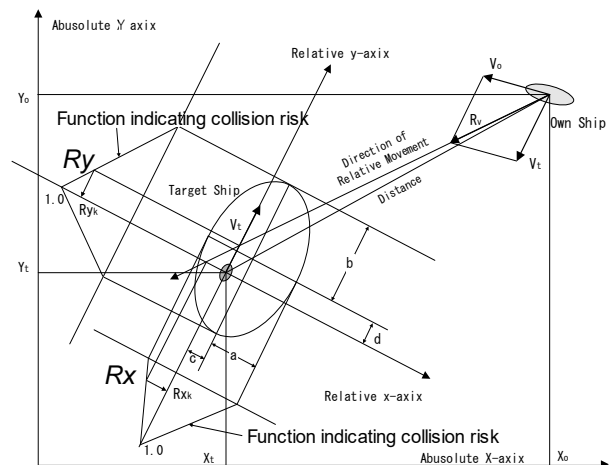
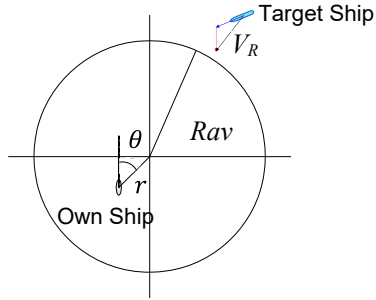


Figure 2. The basic idea how to calculate the collision risk by using exclusive area



$$Rav = (A \cdot V_R + B) \cdot \sqrt{\frac{L_o^2 + L_t^2}{2}} \quad (3)$$

- Rav : Risk calculation starting distance(m)
- V_R : Relative speed (m/s)
- L_o : Own ship LOA (m)
- L_t : Target ship LOA (m)
- A, B : Coefficient
- r : Coefficient ($r \cong Rav/3$)
- θ : 45 degree

Figure 3. Risk calculation starting distance

Figure 2 shows the basic idea how to calculate the collision risk by using exclusive area which is shown as an ellipse. The size and location of this ellipse ($a, b, c, d,$) were defined by summarizing the results of statistical studies that had been done by the authors [2],[3].

The area where the risk calculation is performed is determined by the size and relative speed of the ship as shown in Figure 3. Taking into account the COLREGs, to calculate the risk of the ship seen on her starboard at an early stage, the ship's position is shifted by a distance r . The risk of collision was defined as followings.

$$R(X_{i,j}) = \text{Max}(R_x, R_y) \cdot \left(1 - \frac{Tcpa}{Wtcpa}\right) \quad (2)$$

In above equation, R_y means the risk in direction of the fore and aft line of a target ship, and R_x means such as the transverse direction. Then the larger one was adopted as the risk of collision on such manoeuvre; $X_{i,j}$. ($R_x, R_y; 0$: No risk, 1 : Maximum risk). And further, a margin of Time to Closest Point to Approach ($Tcpa$) was considered as a ratio of type to a certain constant time; $Wtcpa$. Figure 4 shows the degree of risk in the collision avoidance manoeuvring space when there is a crossing situation with a target ship.

2.3 Model of Automatic Collision Avoidance Manoeuvring [3]

In the automatic collision avoidance system, the preference evaluation function for selecting the manoeuvring method is defined by the following equation from the risk shown in Figure 4 and the preference shown in Figure 1. The meaning of this equation is to subtract Figure 1 to Figure 4.

$$Ev(X_{i,j}) = Pb(X_{i,j}) - \alpha \cdot \max_{k=1,m} \{R(X_{i,j})\} \quad (4)$$

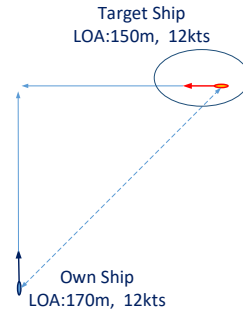
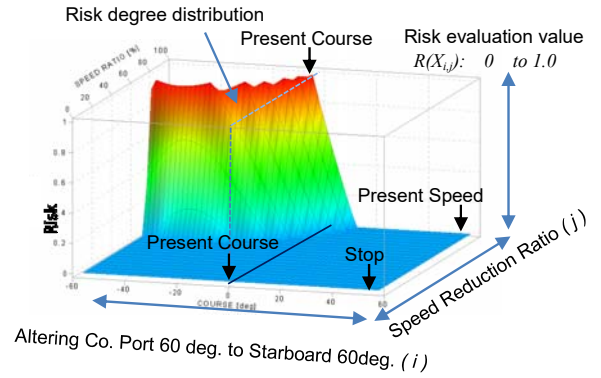


Figure 4. The degree of risk in the collision avoidance manoeuvring space when there is a crossing situation with a target ship: $\max\{R(X_{i,j})\}$

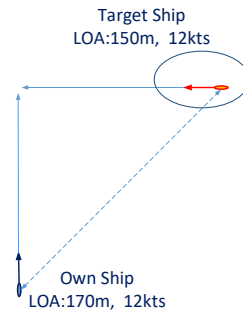
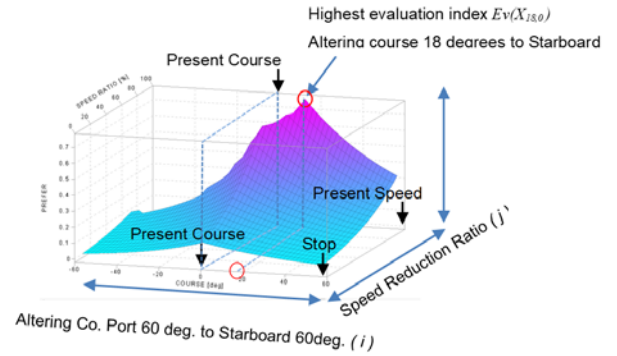


Figure 5. Distribution chart of the preference evaluation index of each manoeuvre: $Ev(X_{i,j})$

The second term of a right side means that the maximum risk value of targets in encounter situation (the number of vessels $k=1$ to m) and α is a coefficient to adjust the relation between a preference and a risk. According to the definitions mentioned above, distribution chart of the preference evaluation index of each manoeuvre are shown in Figure 5. This Figure

5 is obtained by subtracting Figure 1 to Figure 4 in the manoeuvring space according to the expression (4). (Here, $\alpha = 1$)

In the automatic collision avoidance system, the manoeuvring method $X_{i,j}$ having the highest preference evaluation index $Ev(X_{i,j})$ is selected. In the example in Figure 5, it is altering course 18 degrees to starboard at the present speed. Although detailed description is omitted here, other matters considered in this system are briefly described below. The manoeuvrability of the ship is taken into consideration in the risk calculation process. Also, when directing the course to the next waypoint, it is considered in the calculation process of the preference of the manoeuvring method.

3 EVALUATION METHOD OF COLLISION AVOIDANCE MANOEUVRING RESULTS [2]

According to the research by the authors, the main factors for the navigator to recognize the risk of collision with other ships are the relative distance between the own ship and other ships, the rate of change in bearing, the bow crossing, the stern crossing, and the crossing direction. Therefore, the authors propose a method of defining "Danger area", "Caution area", "Safety area" with relative distance and bearing change rate shown in Figure 6 as an index for evaluating the collision avoidance manoeuvring result. In order to create this area, it was formulated in an experiment with a simulator in which 12 Captains and Pilots participated. Experiments were conducted using 135 encounter scenarios and formulated from the results. The total number of data reaches approximately 30,000 points.

For the evaluation of the collision avoidance manoeuvring result, calculate it as '-2' for weighting coefficient when the ship enters 'Dangerous area', '-1' for 'Caution area', '0' for 'safety area'. Specifically, it is expressed by the following expression.

$$Score = \frac{\sum_{t=0}^{t_{end}} -(2 \cdot Dangerous_t + 1 \cdot Cautionary_t)}{t_{end}} \cdot 100 \quad (5)$$

where

Score: Evaluation score (Deduction point) 0 points if there is no danger, minus points increase if many dangerous situations occur.

Dangerous_t: Period/time that existed in the danger area (sec.)

Cautionary_t: Period/time that existed in the caution area (sec.)

t_{end}: Period/time of ship manoeuvring (sec.)

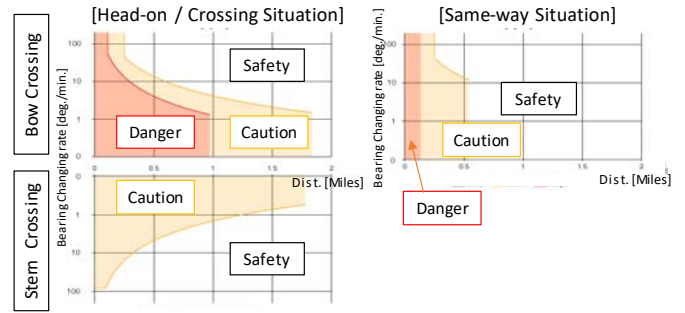


Figure 6. The evaluation area diagram (The "Danger area", "Caution area", and "Safety area" defined by the relative distance and rate of change of the bearings)

4 PARAMETER SETTING FOR CONDUCTING AUTOMATIC COLLISION AVOIDANCE MANOEUVRING THAT DOES NOT GIVE ANXIETY TO THE TARGET SHIP

The manoeuvring method using the automatic collision avoidance system developed this time is depend on the parameters set in Figure 1 to 3 and Equations 1 to 3 etc. These parameters are basically set as a function of the degree of BC: Blocking Coefficient that represents the degree of congestion [3]. The authors point out that it is important not to give anxiety to the target ship to be avoided in setting parameters. In order not to give anxiety to target vessels, it can be rephrased as not to enter the "Danger area" and the "Caution area" in the evaluation area diagram shown in Figure 6.

Examples of the difference in collision avoidance manoeuvring method due to the difference in parameter setting will be shown below. The situation when the bow crossing distance was 1.2 miles as a result of the collision avoidance manoeuvre is shown in Figure 7. Figure 8 shows the situation of seeing own ship from the other target ship at the same time. Figure 9 shows the situation in the evaluation area diagram shown in the previous section. The bow crossing distance is 1.2 miles, the bearing changing rate is sufficient, it is not a situation that gives anxiety to the target ship.



Figure 7. The situation when the bow crossing distance was 1.2 miles as a result of the collision avoidance manoeuvre (Manoeuvring using a simulator)



Figure 8. The situation of seeing own ship from the other target ship at the same time.



Figure 11. The situation of seeing own ship from the other target ship at the same time. (Situation still shows own ship starboard side to the other target ship at the distance is 0.4mile)

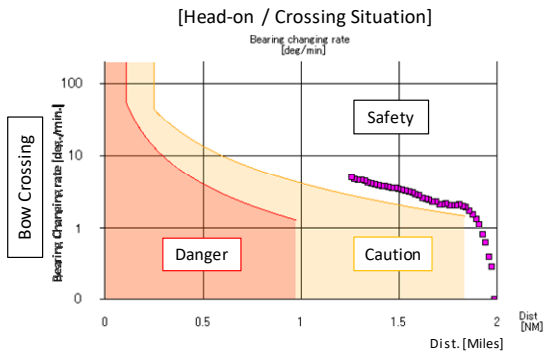


Figure 9. The evaluation area diagram, Bow crossing 1.2miles

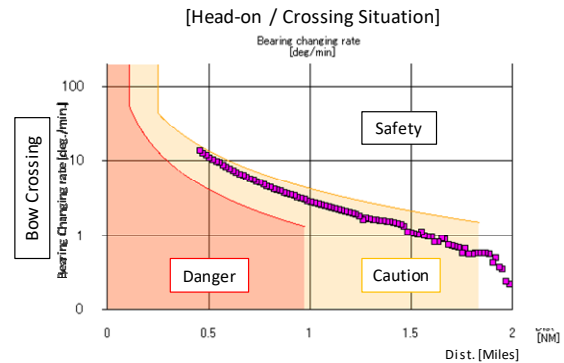


Figure 12. The evaluation area diagram, Bow crossing 0.4miles

Figure 10 shows a view of the situation at the bow crossing distance 0.4 miles as a result of collision avoidance manoeuvring. And Figure 11 shows the situation of seeing own ship from the other target ship at the same time. Figure 12 shows the evaluation area diagram. All plots are evaluations of "Caution area". In Figure 11, it is a situation still shows own ship starboard side to the other target ship at the distance is 0.4mile. It can be said that it is a situation giving anxiety though collision can be avoided. In the automatic collision avoidance system proposed in this paper, the parameters are set so as to avoid collision without giving anxiety as shown in Figure 10 to Figure 12. In other words, parameters were set not to enter the "danger area" or "Caution area" in the evaluation area diagram.

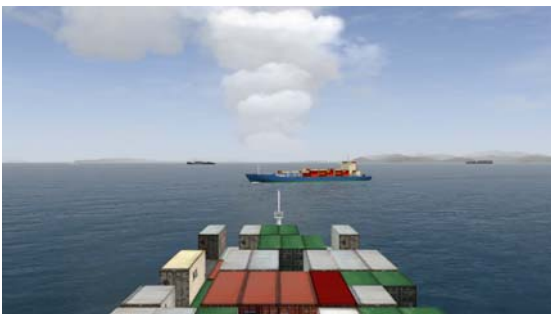


Figure 10. The situation when the bow crossing distance was 0.4 miles as a result of the collision avoidance manoeuvre (Manoeuvring using a simulator)

5 COMPARISON OF MANOEUVRING RESULTS BY AUTOMATIC COLLISION AVOIDANCE SYSTEM AND MANOEUVRING RESULT BY HUMAN

Verification experiments were carried out using a full mission simulator manufactured by Japan Marine Science (JMS). The photograph of the full mission simulator to be used in this study is shown in Figure 13. The angle of visibility of the full mission simulator is 360°, and it is capable of reproducibility in the downward direction as well. In addition, the JMS full mission simulator uses a high-resolution projector (4 times the resolution of a normal high-definition television: 4 K).

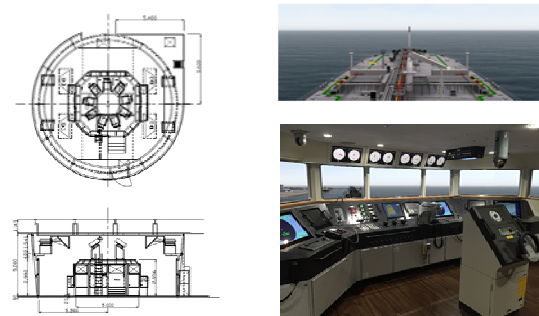


Figure 13. Full mission simulator used in this study (Japan Marine Science made)

Experimental scenario in actual congested sea area is shown in Figure 14. It is a real congestion sea area in the coast of Japan. In order to head to Osaka bay, the own ship encounters many crossing vessels and

sets <056> as the initial course and then alters her course to <020>, <003>. It is a difficult scenario to alter her course while avoiding crossing vessels from her starboard side and port side. In the experiment, automatic collision avoidance system is acquiring data of other vessels from automatic identification system (AIS).

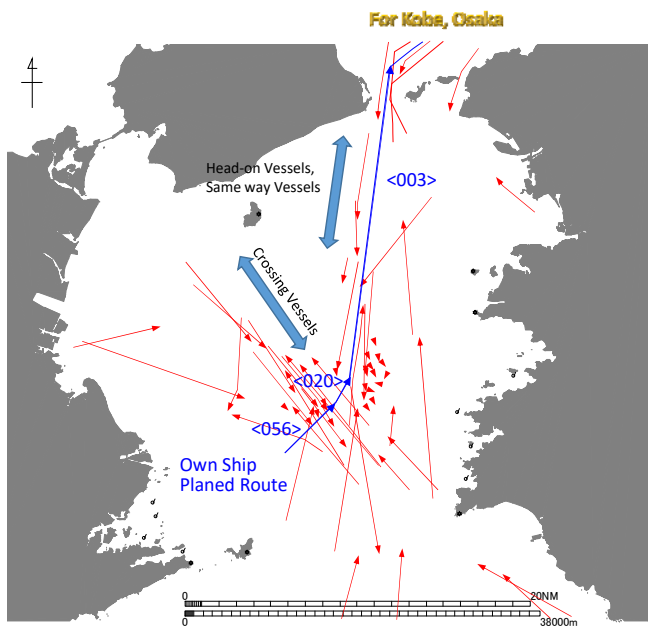


Figure 14. The scenario in which verification experiments were carried out (A real congestion sea area in the coast of Japan)

Figure 15 shows the results ship track chart and relative track chart of collision avoidance manoeuvring by the automatic system. Figure 16 shows collision avoidance manoeuvring by veteran captain. Figure 17 shows collision avoidance manoeuvring by inexperienced officer. Figure 18 shows the situation of relative distance and bearing change rate of all encounter vessels in Evaluation area diagram. Evaluation points (deduction points) calculated by Equation (5) are shown in Table 1. There was a deduction only for manoeuvring by an inexperienced officer. There was no deduction point in manoeuvring of the automatic system and the veteran captain.

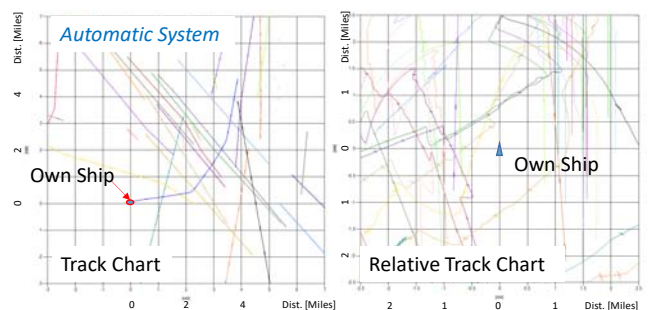


Figure 15. The results ship track chart and relative track chart of collision avoidance manoeuvring by the automatic system

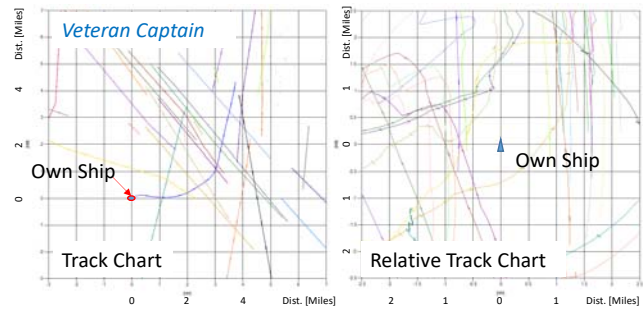


Figure 16. The results ship track chart and relative track chart of collision avoidance manoeuvring by veteran captain

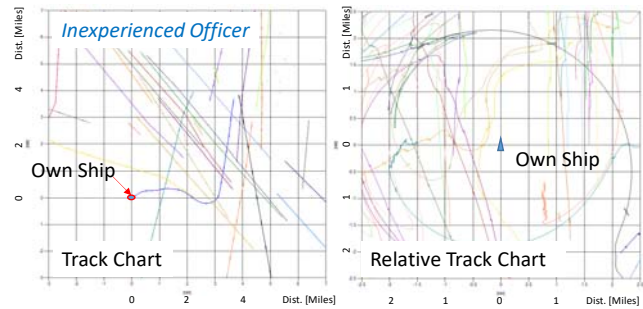


Figure 17. The results ship track chart and relative track chart of collision avoidance manoeuvring by inexperienced officer

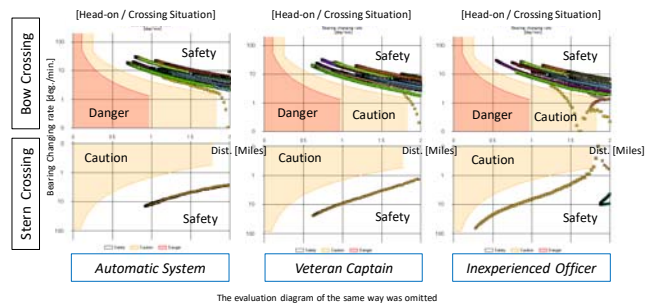


Figure 18. The situation of relative distance and bearing change rate of all encounter vessels in Evaluation area diagram

Table 1. Evaluation points (Deduction points)

	Automatic System	Veteran Captain	Inexperienced Officer
Score	-0.0	-0.0	-5.7

When comparing the own ship's track chart, human steering is deviated to the larger than the manoeuvring by the automatic system in order to avoid the crossing vessels. The automatic system constantly calculates the optimum course for all vessels in the area shown in Figure 3 as well as in the immediate dangerous vessel. As a result, even if there were many crossing vessels from the starboard, the deviation was relatively small. Comparing the navigation between the automatic system and the veteran captain, the own ship's track chart is slightly different, but neither has a deduction point and it is judged that it was almost equivalent manoeuvring. Veteran captain and the automatic system only

avoided the two crossing vessels from the starboard side, but inexperienced officer delayed his judgment and also avoided the third crossing vessel. As a result, the deviation became bigger and the evaluation of the crossing vessels entered the "Caution area" and a deduction occurred.

6 VERIFICATION EXPERIMENT ON ACTUAL SHIP

Validation experiments were conducted to verify the effectiveness of the automatic collision avoidance system on actual ship navigating congested waters in Japan's coastal waters. The verification experiment was conducted for 3 days. The main Particulars and photographs of "Kouzan Maru" boarded for the experiment are shown in Figure 19.



Figure 19. "Kouzan Maru" boarded for the experiment

In the verification experiment on a real ship, risk calculation was carried out using mainly AIS information. At the time of navigating in congested water area, AIS information reached about 500 ships, but there was no problem in processing in real time. Figure 20 shows the view of the on-board experiment off the coast of Yokohama immediately after leaving Tokyo. The track chart and relative track chart sailing off the coast of Yokohama according to the instruction by the automatic collision avoidance system are shown in figure 21.



Figure 20. The view of the experiment off the coast of Yokohama immediately after leaving Tokyo

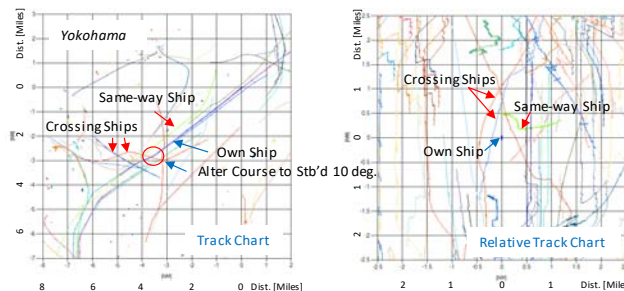


Figure 21. The track chart and relative track chart sailing off the coast of Yokohama (Automatic Manoeuvring)

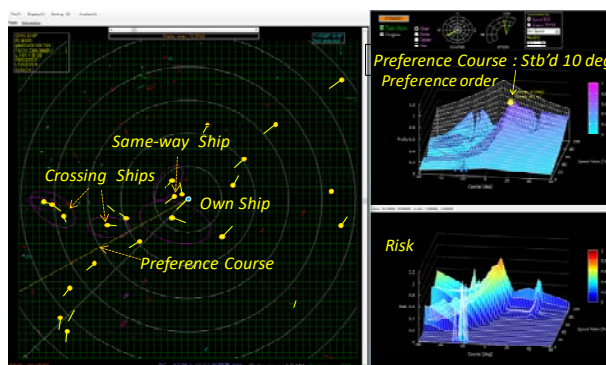


Figure 22. A picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard (Sailing off Yokohama)

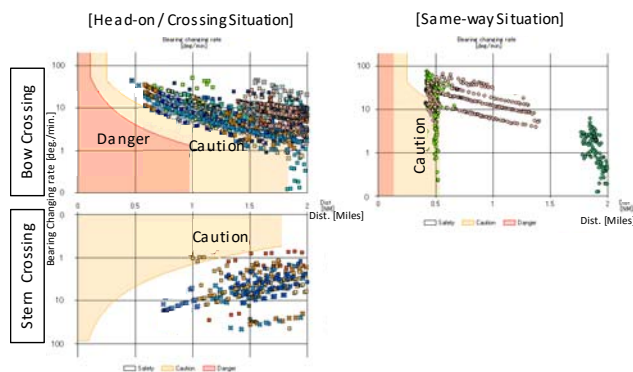


Figure 23. The result in the evaluation area diagram (Distance and bearing change rate), sailing off Yokohama

A picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard is shown in Figure 22. It is a situation where crossing ships from the starboard side are encountered with the manoeuvring area being restricted by same-way ships. The instruction of the automatic collision avoidance system is an altering course to starboard 10 degrees. The evaluation result in the evaluation area diagram (Distance and bearing change rate) in the same area is shown in Figure 23.

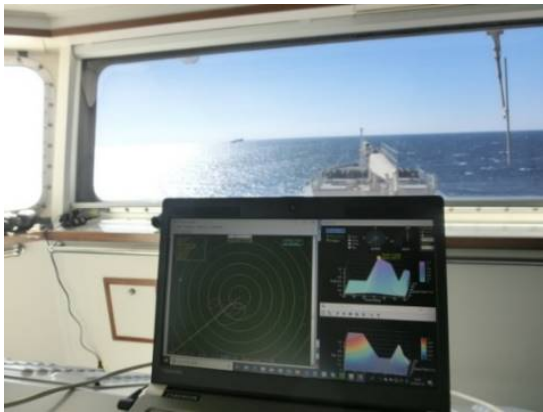


Figure 24. The view of the experiments in areas with relatively high congested water around Japan coast

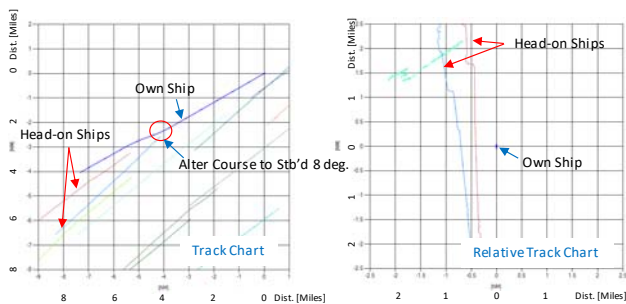


Figure 25. The track chart and relative track chart in the situation of encounter with head-on ships

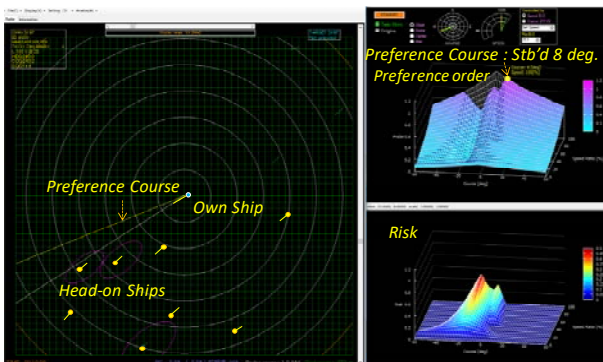


Figure 26. A picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard (in the situation of encounter with head-on ships)

Figure 24 shows the view of the experiments in areas with relatively high congested water around Japan coast. In the situation of encounter with head-on ships, the track chart and the relative track chart is shown in Figure 25. Figure 26 shows a picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard to avoid end on target ships. And the evaluation result in the evaluation area diagram (Distance and bearing change rate) is shown in Figure 27. A sufficient distance and bearing change rate can be secured.

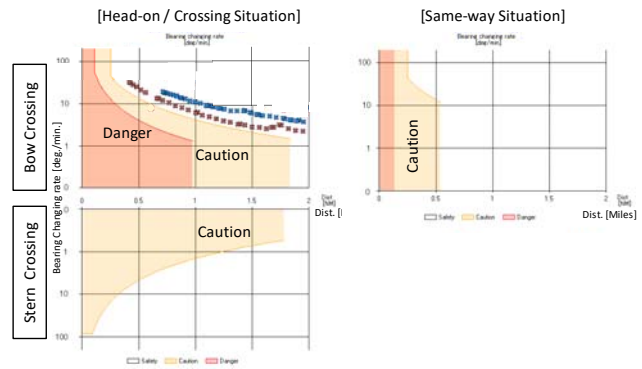


Figure 27. The result in the evaluation area diagram (Distance and bearing change rate), in the situation of encounter with head-on ships

The comments of Master of "Kouzan Maru" are as follows.

- There is no discomfort in the collision avoidance manoeuvring method instructed by the automatic system.
- Captain himself makes a bigger course change in order to clearly show the intention of avoiding own ship to the target ship, compared with the automatic system. (In case of Figure 26)
- A system that graphically displays the status of risk calculation to the operator is effective as a navigation assistance device.

7 CONCLUSION

Main findings obtained by this study are described below.

- In order to carry out strategic collision avoidance manoeuvring, an automatic collision avoidance system constantly calculating optimal manoeuvring method was introduced.
- A system that evaluates the situation that entered "Danger area" and "Caution area" using the relative distance and bearing change rate with a deduction-based evaluation system was proposed.
- It was introduced that the parameters for the proposed automatic collision avoidance system were set so as to avoid collision without giving anxiety to the target other ships.
- Validity verification of the developed automatic collision avoidance system was carried out compared to the manoeuvring results of veteran captain and officers. It was verified that the collision avoidance manoeuvring by the automatic collision avoidance system is almost equal to that by veteran captain.
- Compared to human steering, the automatic system constantly calculates the optimum course, which suggests that there is a tendency for less deviation from the planned route.
- Verification experiments were successfully conducted to verify the effectiveness of the proposed automatic collision avoidance system on the actual ship navigating in congested waters.
- It was confirmed that the manoeuvring method instructed by the automatic collision avoidance system has no discomfort for Master and officers.
- Master of "Kouzan Maru" who joined the experiment commented that he himself would

make a bigger course change in order to clearly show the intention of avoiding own ship to the head-on target ship, compared with the automatic system. This is a future study topic.

- It was confirmed that graphically displays the status of risk calculation to the operator is effective as a navigation assistance device.
- In this experiment, other ships information was acquired only by AIS. It is necessary to consider incorporation of radar information in order to obtain information on vessels, obstacles etc. not equipped with AIS. In the next experiment on the actual ship, authors plan to incorporate radar information.

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