Study on Automatic Collision Avoidance System and Method for Evaluating Collision Avoidance Manoeuvring Results

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Abstract. The authors have two goals that want to achieve. One is development of an automatic collision avoidance system for unmanned autonomous ships. And the other one is development of evaluation method of automatic collision avoidance manoeuvring results. In this paper, the outline of the developed automatic collision avoidance system and the result of the verification test on the actual ship navigating in congested waters are introduced. And also a discussion of the relationship between COLREGs and the desirable automatic collision avoidance system and methods for quantitatively assessing the desirable automatic collision avoidance system are introduced. In addition, quantitative comparison by the proposed evaluation system between the manoeuvring results of the automatic collision avoidance system and the veteran captain's manoeuvring results are introduced.

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. The authors have two final goals that want to achieve. One is development of an automatic collision avoidance system for unmanned autonomous ships controlled from a shore base. And the other one is development of evaluation method of automatic collision avoidance manoeuvring results.

The automatic collision avoidance 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 ships controlled from a shore base.

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.

In addition, the authors proposed a method to quantitatively evaluate the desirable automatic collision avoidance manoeuvring results.

2. Basic Concept of Automatic Collision Avoidance Manoeuvring

2.1. Strategic Collision Avoidance Manoeuvring

There are many vague expressions in the current COLREGs. For example, the following description is given in Rule 17: Action by stand-on vessel. "…The vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision". It can be said that it is quite dangerous that this rule is applied. Therefore, the desirable automatic system takes action to reduce the risk before the "Conduct of Vessels in Sight of Another" defined by the COLREGs is applied. In other words, it should be avoided that the rules of “Action by stand-on vessel” apply.

Therefore, 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. The automatic collision avoidance system for realizing the strategic collision avoidance manoeuvring proposed by the authors is altering her course or changing her speed to reduce the risk basically before rules defined by CORLEGs is applied

2.2. Calculation of Collision Risk and Preference in the Collision Avoidance Manoeuvring Space [1]

When a navigator decides the method to prevent a collision, two principal factors 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 \((X_{ij})\). The horizontal axis is a course \((i)\), the longitudinal axis is a speed \((j)\) and the evaluation value of each manoeuvre \((Pb(X_{ij}))\) 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:

\[
Pb(X_{i,0}) = \exp(-a_c \cdot \Delta Co) \]

\[
Pb(X_{0,j}) = \exp(-a_v \cdot \Delta V) \]

\[
Pb(X_{i,j}) = Pb(X_{i,0}) \cdot Pb(X_{0,j}) \] (1)

Where, \(Pb(X_{i,j})\) is evaluation value of preference of manoeuvre \(X_{i,j}\), \(\Delta Co\) is degree of altering course, \(\Delta V\) 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 2 shows the basic idea how to calculate the collision risk by using exclusive area which is shown as an ellipse. The coefficients that determine the size of this ellipse will be described in Chapter 4.

\[
R(X_{ij}) = \max\left( R_x, R_y \right) \cdot \left( 1 - \frac{Tcpa}{Wtcpa} \right)
\]  

(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; \(X_{ij}\). (\(R_x, R_y; 0: \text{No risk, 1: Maximum risk}\)). 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 3 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

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 3 and the preference shown in Figure 1. The meaning of this equation is to subtract Figure 3 from Figure 1.
\[ Ev\left(X_{i,j}\right) = Pb\left(X_{i,j}\right) - \alpha \cdot \max_{k=l}^{m} \left[R\left(X_{i,j}\right)\right] \] (3)

The second term of a right side means that the maximum risk value of targets in encounter situation (the number of vessels $k=l$ to $m$) and $\alpha$ 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 4. This Figure 4 is obtained by subtracting Figure 3 from Figure 1 in the manoeuvring space according to the expression (3). (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 4, it is altering course 18 degrees to starboard at the present speed.

**Figure 4.** Distribution chart of the preference evaluation index of each manoeuvre: $Ev(X_{i,j})$

### 3. Evaluation Method of Collision Avoidance Manoeuvring Results

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 5 as an index for evaluating the collision avoidance manoeuvring result. Details of the evaluation formula and definition of evaluation areas are shown in Table 1. 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.[2] Moreover, in order to evaluate the manoeuvring method to reduce the risk before CORLEGs "Action by stand-on vessel" described in the previous chapter is applied, in addition to the conventional research, additional experiment was performed and the evaluation chart of the crossing vessel from the port was newly added. 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.

\[ Score = \sum_{t=0}^{t_{end}} \frac{(2 \cdot Dangerous + 1 \cdot Cautionary)}{t_{end}} \cdot 100 \] (4)

where

- **Score**: Evaluation score (Deduction point)
- 0 points if there is no danger, minus points increase if many dangerous situations occur.
- **Dangerous**: Period/time that existed in the danger area (sec.)
- **Cautionary**: Period/time that existed in the caution area (sec.)
- **tend**: Period/time of ship manoeuvring (sec.)
Figure 5. The evaluation area diagram (The “Danger area”, “Caution area”, and “Safety area” defined by the relative distance and rate of change of the bearings)

| Encounter situation | Evaluation formula | Evaluation |
|---------------------|--------------------|------------|
| **Head-on**         |                    |            |
| **Bow Crossing**    | \( \theta < \infty \) & \( R < 185.2 \text{ [m]} \) | Danger |
|                     | \( \theta \leq 4.5 \times 10^5 \cdot R^{-1.7} \) & \( R < 1852.0 \text{ [m]} \) | **Caution** |
| Stern Crossing      | \( \theta < \infty \) & \( R < 463.0 \text{ [m]} \) | **Safety** |
|                     | \( \theta \leq 15.0 \times 10^5 \cdot R^{-1.7} \) & \( R < 3,426.2 \text{ [m]} \) |            |
| Range excluding danger area and caution area | | |
| **Same-way**        |                    |            |
| **Bow Crossing**    | \( \theta < \infty \) & \( R < 1852.0 \text{ [m]} \) | Danger |
|                     | \( \theta \leq 4.5 \times 10^5 \cdot R^{-1.7} \) & \( R < 1852.0 \text{ [m]} \) | **Caution** |
| Stern Crossing      | \( \theta < \infty \) & \( R < 463.0 \text{ [m]} \) | **Safety** |
|                     | \( \theta \leq 15.0 \times 10^5 \cdot R^{-1.7} \) & \( R < 3,426.2 \text{ [m]} \) |            |
| Range excluding caution area | | |
| **Crossing from Port** | | |
| **Bow Crossing**    | \( \theta < \infty \) & \( R < 1852.0 \text{ [m]} \) | Danger |
|                     | \( \theta \leq 4.5 \times 10^5 \cdot R^{-1.7} \) & \( R < 1852.0 \text{ [m]} \) | **Caution** |
| Stern Crossing      | \( \theta < \infty \) & \( R < 463.0 \text{ [m]} \) | **Safety** |
|                     | \( \theta \leq 15.0 \times 10^5 \cdot R^{-1.7} \) & \( R < 1852.0 \text{ [m]} \) | **Caution** |
| Range excluding danger area and caution area | | |

\( \theta \): Rate of change in bearing (deg./min.)  
R: Relative distance (m)

**Danger**: Unacceptable area  
**Caution**: The area where own ship commence to avoid or expect another ship to avoid  
**Safety**: Acceptable area
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 2 and Equations 1 to 2 etc. These parameters are basically set as a function of the degree of BC: Blocking Coefficient that represents the degree of congestion [1]. 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 5.

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 6. Figure 7 shows the situation of seeing own ship from the other target ship at the same time. Figure 8 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 6. The situation when the bow crossing distance was 1.2 miles as a result of the collision avoidance manoeuvre (Manoeuvring using a simulator)

Figure 7. The situation of seeing own ship from the other target ship at the same time.

Figure 8. The evaluation area diagram, Bow crossing 1.2miles

Figure 9 shows a view of the situation at the bow crossing distance 0.4 miles as a result of collision avoidance manoeuvring. And Figure 10 shows the situation of seeing own ship from the other target ship at the same time. Figure 11 shows the evaluation area diagram. All plots are evaluations of “Caution area”. In Figure 10, 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. It is common evaluation of all three captains who participated in the verification experiment.

In the automatic collision avoidance system proposed this paper, the parameters are set so as to avoid collision without giving anxiety as shown in Figure 6 to Figure 8. In other words, parameters were set not to enter the “danger area” or “Caution area” in the proposed evaluation area diagram.
Figure 9. The situation when the bow crossing distance was 0.4 miles as a result of the collision avoidance manoeuvre (Manoeuvring using a simulator)

Figure 10. 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 11. The evaluation area diagram, Bow crossing 0.4miles

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 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).

Experimental scenario in actual congested sea area is shown in Figure 12. 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 13 shows the results ship track chart a of collision avoidance manoeuvring by the automatic system. Figure 14 shows collision avoidance manoeuvring by veteran captain. When comparing the own ship's track chart, There is no big difference between an automatic system and a veteran captain. Figure 15 shows the situation of relative distance and bearing change rate of all encounter vessels in Evaluation area diagram manoeuvring by the automatic system. Figure 16 is also the evaluation of the result of manoeuvring by the veteran captain. Both the manoeuvring of the automatic system and the manoeuvring of the veteran captain have no deduction points for the crossing ship from the starboard side. Veteran captain's manoeuvring has a slightly larger deduction point for the crossing ship from the port side. This was due to the fact that the veteran captain was avoiding crossing ships from the starboard side, so he did not pay attention to the ships from the port about eight miles away. Therefore, although it was slight, a deduction occurred. It is the place shown by the arrow in Figure 14 and Figure 15. The automatic collision avoidance system calculates the risk of all vessels within the set range. Although the risk weighting is taken into account, the system does not calculate only the immediate
danger. Compared to humans, automatic systems are better at preventing "lack of situational awareness".

**Figure 12.** The scenario in which verification experiments were carried out (A real congestion sea area in the coast of Japan)

**Figure 13.** The results ship track chart of collision avoidance manoeuvring by the automatic system

**Figure 14.** The results ship track chart of collision avoidance manoeuvring by veteran captain

**Figure 15.** The situation of relative distance and bearing change rate of all encounter vessels in Evaluation area diagram (manoeuvring by the automatic system)

**Figure 16.** The situation of relative distance and bearing change rate of all encounter vessels in Evaluation area diagram (manoeuvring by veteran captain)
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 2 days. The main particulars and photographs of "Kouzan Maru" boarded for the experiment are shown in Figure 17. Tracks of encounter ships captured by AIS is shown in Figure 18. There were 5,911 ships encountered in 2 days.

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 19 shows the view of the on-board experiment off the coast of Yokohama immediately after leaving Tokyo. A picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard is shown in Figure 20. 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 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. The evaluation result in the evaluation area diagram (Distance and bearing change rate) in the same area is shown in Figure 22. It was a congested area but no points were deducted. Many plots are found near the boundaries of the caution and safety area.
Figure 21. The track chart and relative track chart sailing off the coast of Yokohama (Automatic Manoeuvring)

Figure 22. The result in the evaluation area diagram (Distance and bearing change rate), sailing off Yokohama

Figure 23 shows the view of the experiments in areas with relatively high congested water around Japan coast (Off Mie).

Figure 23. The view of the experiments in areas with relatively high congested water around Japan coast (Sailing off Mie)

Figure 24. 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 a picture of a situation where the automatic collision avoidance system instructs to alter her course to starboard to avoid head-on target ships. In the situation of encounter with head-on ships, the track chart and the relative track chart is shown in Figure 25. And the evaluation result in the evaluation area diagram (Distance and bearing change rate) is shown in Figure 26. A sufficient distance and bearing change rate can be secured. A sufficient change in bearing can be seen at a distance of 2 miles. It shows that strategic collision avoidance manoeuvring has been carried out.

![Track Chart and Relative Track Chart](image1)

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

![Evaluation Area Diagram](image2)

**Figure 26.** The result in the evaluation area diagram (Distance and bearing change rate), in the situation of encounter with head-on ships

7. **Conclusion**

Main findings obtained by this study are described below.

- Proposed that as an automatic collision avoidance system, a "strategic collision avoidance manoeuvring" would be desirable to reduce the risk before COLREGs is applied.
- 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.
- The proposed evaluation system is effective to evaluate the desired level of the automatic collision avoidance system.
• Validity verification of the developed automatic collision avoidance system was carried out compared to the manoeuvring results of veteran captain.
• 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 is better at preventing "lack of situational awareness".
• Verification experiments were successfully conducted to verify the effectiveness of the proposed automatic collision avoidance system on the actual ship navigating in congested waters.
• 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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