Multi-ship Collision Avoidance Control Strategy in Close-quarters Situations: a Case Study of Dover Strait Ferry Maneuvering

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***Abstract*—Multi-ship collision avoidance is challenging in busy waters like the Dover Strait. Usually, ships follow the rules for avoiding collisions which are given by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), by the International Maritime Organization (IMO). However, COLREGS can be ambiguous to follow in the close-quarters situations due to the complex crossing scenarios. In that situations, multiple ship avoid collisions with each other is highly dependent upon seamanship and crew's experience. In this study, we propose a COLREGS-compliant decision making strategy that integrates the human expertise with the artificial intelligent method. A simulation scenario was utilized to validate the effectiveness and feasibility of the proposed method.**

***Index Terms*—Multi-ship collision avoidance, Traffic separation scheme (TSS), COLREGs-compliant**

I. INTRODUCTION

Ship collision carries serious consequences. What are the reasons for conducting the incidents? In a major literature study by The Nautical Institute [1], the causes of collisions were identified and compared in percentage terms. It can be seen in the context of managing the risks that lack awareness of the other vessel, poor lookout, and insufficient assessment of situation account for 60%. Most of the marine accidents can be traced to human errors. Another more detailed survey carried out by [2], studied 100 written accident reports from the maritime authority and concluded that the most frequently involved unsafe acts in a collision is poor lookout. The underlying human element is lack of experience, knowledge, and correct application of the International Regulations for the Prevention of Collisions at Sea 1972 (COLREGS) [3]. These regulations are designed to give guidance to the crew in charge of the ships in order to manage the collision risk. COLREGS are a significant mechanism by which navigational risk is controlled. If the rules are not followed then the collision risk is increasing corresponding.

Recently, with increasing traffic densities and the average cruising speed, a collision in busy waters can be catastrophic and, like the motorway, the outcome of the one collision can lead to a "pile-up" involving other ships colliding with the wreck. As shown in Fig. 1, several passenger ferryboats (deep blue) transit through the Traffic Separation Scheme (TSS) area

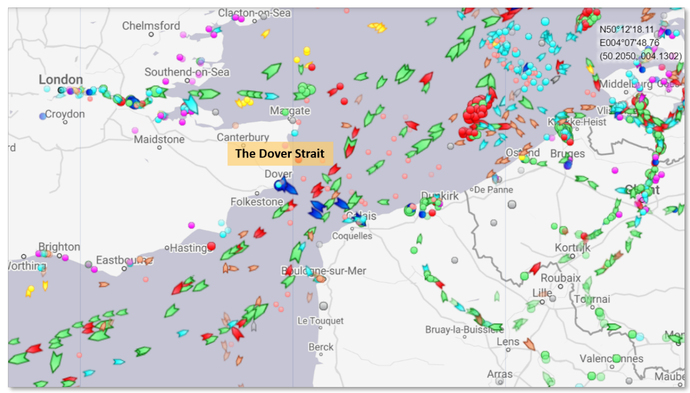

Fig. 1: Traffic Separation Scheme (TSS) areas in Dover Strait AIS Screenshot from MarineTraffic.com.

in the Strait of Dover. In spite of its narrowness, it is the most busiest maritime route in the world. Statistically, it is estimated that the Dover Strait sees the passage of around 400 ships on an everyday basis. When transiting the Dover Strait TSS area, the officer on watch (OOW) on ferryboats should maintain a sensitive and wide lookout at all times to measure collision risk as there is generally considerable crossing traffic, then take a correct action as early as possible comply with COLREGS. [4] reviews collision risk related research in these high density-traffic areas. Also, a number of multi-ship collision avoidance approaches considering the COLREGs have been proposed over the few years. That includes algorithms including model-based methods, like model predictive control ([5] [6] [7]), and model-free control method, such as reinforcement learning (RL)([8]).

Different from maneuvering in open water, the OOW should consider additional factors in the high dense traffic areas. For example, vessels crossing TSS areas must do so at right angles. This provision can lead to confusion if the crossing vessel elects to maneuver along the edge of the scheme before turning. Moreover, when fail to appreciate that avoidance action taken by one ship to avoid another could place its own ship in a collision risk situation due to the limited time to response situation [9]. The aforementioned evidence indicates that maneuvering in the closed range is more complicated than in the open water. A large proportion accident occurs in TSS area with misinterpreting of the current situation and failing to take the correct action. To reduce the collision risk in these areas, a COLREGs-compliant collision avoidance system (CAS) is intensely required. It is expected to help the captain to improve their prediction for the surrounding environment and decision-making capabilities.

However, it is a fact that COLREGS can only ever dictate hypothetically, the actions to be taken between two vessels, while in the real world there are occasions when more than one vessel may be a collision risk at the same time. The OOW is forced to prioritize, deciding what actions to be taken. COLREGS define what action to take, but end on encounters can be ambiguous and because both vessels are expected to take action the outcome is not always predictable. For example, Rule 17 states “When, from any cause, 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 is very general but does not guide what is “so close”. That requires a trained response to these developing situations, which highly rely upon good seamanship and experience. [3] As a result,

- Are there any methods to quantize the ambiguous descriptions in COLREGS rules?
- How to integrate the rules, empirical knowledge, and experience into the system?
- Is there any way to fully observe the environment change and make a prediction on it?

To solve the problems, [10] analysis the CORLEGS using the statistic method. In this study, we propose a CAS involves multiple ships by integrating COLREG rules and artificial intelligent methods with the following control strategy:

- quantitative analysis of rules and seamanship based on the historical log data from simulator;
- interprete the log data and extract features by statistic method and transfer know-how from experts;
- develop the CAS based on RL by integrating the extracted features.

First, the experts’ demonstrations are collected and labeled from the simulator. We interprete the log data and extract features by statistic method. The value of quantitative analysis of historical data lies in bringing decision-making to a more intelligent level - a level where important decisions are made based on tremendous data, with the minimum possibility of human error and bias. Second, we interview several experienced captains and record the questions and answers, which regarded as a reference for developing the CAS. After transferring know-how from experts, we move to the third stage: training policy of COLREGs-compliant CAS based on RL. Finally, the proposed CAS has the capability of offering various decision supports in different operational scenarios. Meanwhile, the optimal trajectory and collision risk with other target ships can be calculated during the training process.

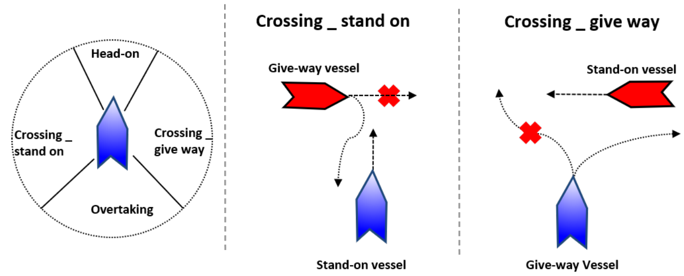

Fig. 2: Illustration of the COLREGs interpretation.

The layout of the paper is as following: Sec. II presents the problem definition of this study. Sec. III proposes method in detail, including the data collecting, collision risk calculation, and RL training process. The implementation and learning results of the simulation are presented in Sec. IV At last, a discussion about the result and the application prospect is given in Sec. V.

II. Problem Formulation

A. COLREGS rule related to TSS

Dover Coastguard gives a conclusion that 48 % of accidents were in crossing situations [11], by recording the number of inter-ship collisions and hazardous incidents. The causes of collisions in Dover Strait TSS are not only because of its complicated maritime traffic but the human factor issues: A lack of knowledge of COLREGS. When ships do not respond within the framework of the rules, high level of unpredictability are introduced. In this study, we focus on the crossing situation for a ferryboat in Dover Strait. The crossing scenario defined by COLREGS is presented in Fig. 2, where the circle illustrates TSs in different relative bearing regions, and have a fixed orientation with respect to the OS.

The relevant rules with respect to collision avoidance in the TSS are presented as follows:

Rule 10 Traffic Separation Schemes:

- (a) This Rule applies to traffic separation schemes adopted by the Organisation and does not relieve any vessel of her obligation under any other Rule.
- (b) A vessel using a traffic separation scheme shall:
  - proceed in the appropriate traffic lane in the general direction of traffic flow for that lane;
  - so far as practicable keep clear of a traffic separation line or separation zone;
  - normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from either side shall do so at as small an angle to the general direction of traffic flow as practicable.
- (c) A vessel shall, so far as practicable, avoid crossing traffic lanes but if obliged to do so shall cross on a heading as nearly as practicable at right angles to the general direction of traffic flow.

Rule 15 Crossing situation:

- When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Rule 16 Action by the give-way vessel:

- Every vessel which is required to keep out of the way of another vessel should take early and large enough action to safely avoid collision.

Rule 17 Action by the stand-on vessel:

- This rule requires that a stand-on vessel should keep its current speed and course. The stand-on vessel may, however, maneuver to avoid collision if it becomes apparent that the give way vessel is not taking appropriate actions to avoid collision. Furthermore, if the stand-on vessel finds itself so close to the obstacle that collision can not be avoided by the give-way vessel alone, the stand on vessel should take such action which best aids to avoid collision. In a crossing situation, the stand on vessel should avoid maneuvering to port, since this could lead to a collision if the give-way vessel maneuvers to starboard.

B. Problem formulation in the Dover Strait TSS

Navigation risk will be reduced and managed by having uniform compliance with COLREGS. It requires the OOW in the ferry the strictly adherence to COLREGS as transiting through the Dover Strait TSS, not only in respect of **Rule 10**, but also **Rule 15**, **Rule 16**, **Rule 17**, and so on.

An example of a crossing situation in TSS is shown in 3. The TSS is designed to create lanes with ships in a specific lane all maneuvering in the same direction. It divided into the Southwest (SW) bound lane and the Northeast (NE) bound lane. Ships are going to or departing from one of the many ports in TSS and the ferries are crossing the Strait. Here, the ferry treats itself as the “own ship” (OS) and other nearby ships as the “target ships” (TSs). According to COLREGS, a ship with the other one to her starboard side is deemed the give-way vessel, while the other vessel is deemed the stand-on vessel. Consequently, in the NE bound lane, target ship 1 (TS1) is assigned as the give-way vessel, while OS is assigned as the stand-on vessel. The give-way vessel TS1 should maneuver to avoid a collision, preferably bypassing behind the stand-on vessel OS, while the OS should keep her speed and course. In the SW bound lane, the situation is the opposite.

At first, the OS has to cross the TSS as near as possible to right angles. So that the TSs have time to assess the intention of the OS. Second, to prevent misinterpreted its intentions by the other ships, the give-way vessel TS1 should take the action as soon as possible, while the stand-on vessel OS has to keep a close eye on the surrounding TSs, until the give-way vessel successfully avoids it. Third, when the OS joins the SW lane, the OS has to alter its course to starboard or speed to avoid the TSs approaching from the north, in accordance with **Rule 15 crossing situation**.

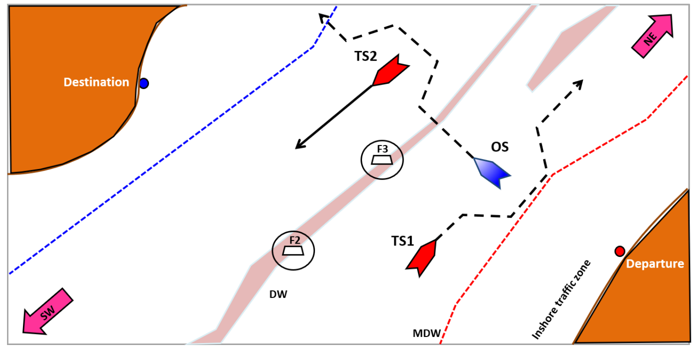

Fig. 3: Crossing situation in the TSS.

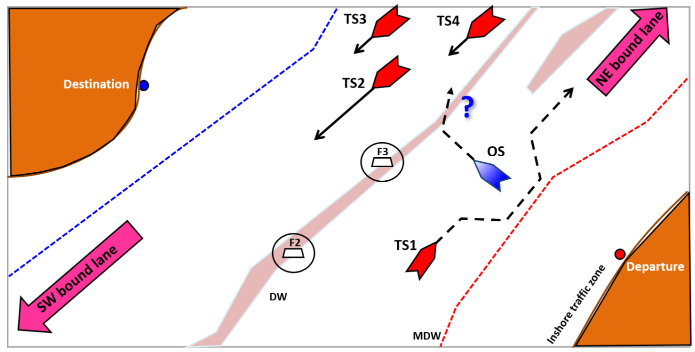

Fig. 4: Multi-ship crossing situation in the TSS.

However, when there are multiple ships continuously approaching from the OS’s starboard side, as presented in Fig. 4. This situation gets serious because it is hard to be predicted if and when the multiple TSs are passed by. It is also common occurs near busy ports. There are probably two ways of dealing with it, one is to wait until the collision risk is zero. That will influence the predefined time schedule. The other is to cruise the edge and wait for a large gap which will allow sufficient time to cross, or assess early and alter early. This would have created another close-quarters situation with an SW going vessel to the south, who would have then had to slow down or alter to starboard. It will undoubtedly increase the risk of multiple ship collisions. In reference to the collision between the Norwegian Dream and the Ever Decent [12]. Moreover, COLREGS does not provide a specifical guide for this kind of situations.

Therefore, concerning the above scenario, we focus on finding an optimal strategy to avoid multiple ships in the TSS area: when a group of TSs approaching from an OS’s starboard side.

III. Method

A. Collision risk management

Collision avoidance of ships is often performed while considering the closest point of approach (CPA). CPA is defined as the closest point of approach of an approaching TSs where the relative course of the approaching target ship is tangential

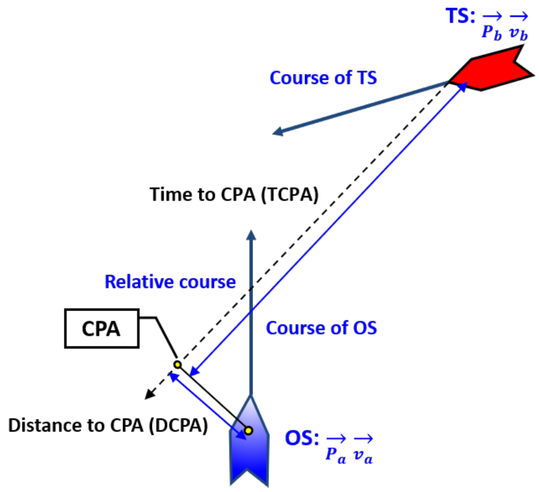

Fig. 5: Illustration of CPA and TCPA.

to the minimise range. Distance to CPA (DCPA) is the distance in miles from the target ship to the CPA. Time to CPA is the time that a target ship will take to reach the CPA. [13] [14]. For instance, in the case of a head on situation, DCPA always has a value close to 0, regardless of the time to collision; For TCPA, regardless of the relative distance between the OS and TS, it is determined by the time to the CPA. As a result, the risk level of an encounter is based on the DCPA and TCPA, in accordance with the explanation in Fig. 5.

The evaluation of DCPA and TCPA can be described mathematically in Equation (1) and Equation (2), where P_a and P_b denote the position vector of the OS and TS; v_a and v_b the velocity vectors of the OS and TS, respectively.

$$\text{TCPA} = \begin{cases} 0 & \text{if} \|\vec{v}_a - \vec{v}_b\| \leq \epsilon \\ \frac{(\vec{P}_a - \vec{P}_b)(\vec{v}_a - \vec{v}_b)}{\|\vec{v}_a - \vec{v}_b\|^2} & \text{otherwise} \end{cases} \tag{1}$$

$$\text{DCPA} = \|(\vec{P}_a + \vec{v}_a \cdot \text{TCPA}) - (\vec{P}_b + \vec{v}_b \cdot \text{TCPA})\| \tag{2}$$

B. Data processing

The multi-ship crossing situation is performed in the simulator by several experts. The definition of the crossing scenario is given in Fig. 4, where the TSs' speed are setup as 14 knots, and OS's speed is 16 knots. The accepted AIS data from the simulator are used to extract the information required for the following RL training and for predicting the movement of the ships. The extracted information includes own ship (OS) and target ship types, latitude, longitude, speed, course over ground, and position. By calculating the range when the ship starts to avoid multiple TSs, the condition for collision avoidance is estimated and presented as follows: the OS alters course substantially between 25° and 30° when TSs reaches a specified range, where the distance to TS1 is $d_1 \in [4\text{NM}, 5\text{NM}]$, the distance to TS2 is $d_2 \in [5\text{NM}, 6\text{NM}]$; the DCPA with TS1, TS2 are $D_1 \in [0.2\text{NM}, 4.5\text{NM}]$, $D_2 \in [0.3\text{NM}, 4.5\text{NM}]$, respectively; the TCPA with TS1, TS2 are $T_1 \in [10\text{min}, 12\text{min}]$, $T_2 \in [12\text{min}, 14\text{min}]$, respectively.

TABLE I: The observation space defined in the DRL algorithm.

Name	Description
y_e	error between OS and the path
$\|\|P_{goal} - P\|\|_2$	distance to the destination
χ_e	OS course error
δ	rudder angle
$\dot{\delta}$	rudder angular velocity
P_{TS_i}	TS position
V_{TS_i}	TS velocity
$\|\|P - P_{TS_i}\|\|_2$	relative distance between OS and TS_i
$\chi - \chi_{TS_i}$	relative course angle between OS and TS_i
L	length of the OS
l_i	length of the TS_i

TABLE II: The action space defined in the DRL algorithm.

Name	Description
δ	rudder angle
v	ship speed

C. Reinforcement learning structure for the CAS

We now present the proposed control method for multiship collision avoidance based on the DRL algorithm. For the specific crossing scenario for the multi-ship, we refine the policy which was trained by our previous study [15].

Training both the critic network and policy network by defining surrogate loss functions for each network [16]. During the training process, the state inputs to the neural networks, and the agent selects and executes an action according to the policy with the highest probability. Then back-propagate gradients computing with the unified surrogate loss function are used to update the weights of the network.

The state and action definitions of this problem are presented in Table. I and Table. II. For each time step t, given the current state x_0, an optimal open-loop control sequence is determined to minimize the loss function. The first control signal u_0 is then applied to the system and then get the next step state x_1, and the reward r_0.

The objective of the OS is to transit the strait at right angle following the predefined path while avoids collision with the TSs. So the reward functions for path following R_{pf} and multi-ship collision avoidance R_{ca} have to be taken into consideration. The extracted features from the data processing are used in the reward function formulation.

IV. Implementation

A. Ship modelling

The equations of the ship manoeuvring model in this study can be written as follows [17]:

$$m(\dot{u} - vr - x_G r^2) = X_H + X_P + X_R \tag{3}$$

$$m(\dot{v} + ur + x_G \dot{r}) = Y_H + Y_P + Y_R \tag{4}$$

$$I_{zz}\dot{r} - m x_G(\dot{v} + ur) = N_H + N_P + N_R \tag{5}$$

$$
\begin{aligned}
X_H &= X(u) + X_{\dot{u}}\dot{u} + X_{vv}v^2 + X_{vr}vr + X_{rr}r^2 && (6)\\
Y_H &= Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{r|r|}r|r| + Y_{v|v|}v|v|Y_{r|v|}r|v| \\
&\quad + Y_{v|r|}|r|v + Y_{vrr}vr^2 + Y_{vvr}rv^2 && (7)\\
N_H &= N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{r|r|}r|r| + N_{v|v|}v|v|N_{r|v|}r|v| \\
&\quad + N_{v|r|}|r|v + N_{vrr}vr^2 + N_{vvr}rv^2 && (8)
\end{aligned}
$$

$$
\begin{aligned}
X_P &= (1-t)\rho n^2 K_T(J_p)x && (9)\\
J_p &= u_{prop}(1-w_p)/nD_p && (10)
\end{aligned}
$$

where the terms X_H, Y_H, and N_H in Eq. 3 represents the hydrodynamic forces. the second term X_P, X_P, and X_P represents the propeller force, X_R, X_R, and X_R represents the rudder forces acting on the ship.

B. Decision making for multi-ship collision avoidance

We outline the decision making process for multi-ship CAS in this section, which presented in Fig. 6. Notice that we assign the OS as the maneuver party and all TSs nearby the OS is denoted as TSs. A four-phase mixed approach was utilized to investigate the mechanism lying behind the decisions taken to manage collision avoidance compliant with COLREGS through the application in the TSS area.

The first phase is to determine whether the encountered TSs are within a safe range of the OS. Then to categorize the type of encountered TSs with a potential collision risk. The procedure of TSs categorization is performed based on the instantaneous positions and relative headings between the OS and each of the TSs. Therefore, the TSs with respect to the OS are denoted as belonging to one of the following four regions: crossing_stand on, overtaking, crossing_give way, and head-on situations, respectively, which refer to [18]. The second phase gets into the collision risk calculation in the crossing situation. For instance, in the SW bound lane area, assume that multiple TSs are approaching to the OS's starboard side. Traffic grouping can be used in the decision-making process in this close-range situation. It can help the captain to estimate a dangerous area well in advance, also gives a clear picture of the situation. After grouping the crossing TSs with high collision risks as group A, then the OOW needs to determine the TSs' DCPA and TCPA.

At this moment, the OOW in the OS needs to keep a careful watch for the crossing ships from the starboard side, assess the situation early, and choose a proper action: adjust speed or alter course in advance. In the following steps, we use the experience of several experts' advice, who introduce that changing speed is often not an effective maneuver in late collision avoidance, especially for larger vessels with high inertia force. If the OS is in a complex sea condition or emergency situation, the speed change is a priority option (condition 1). According to the data processing analysis, some experts make it a requirement to alter course between 25° and 30°, when the collision risks exist.

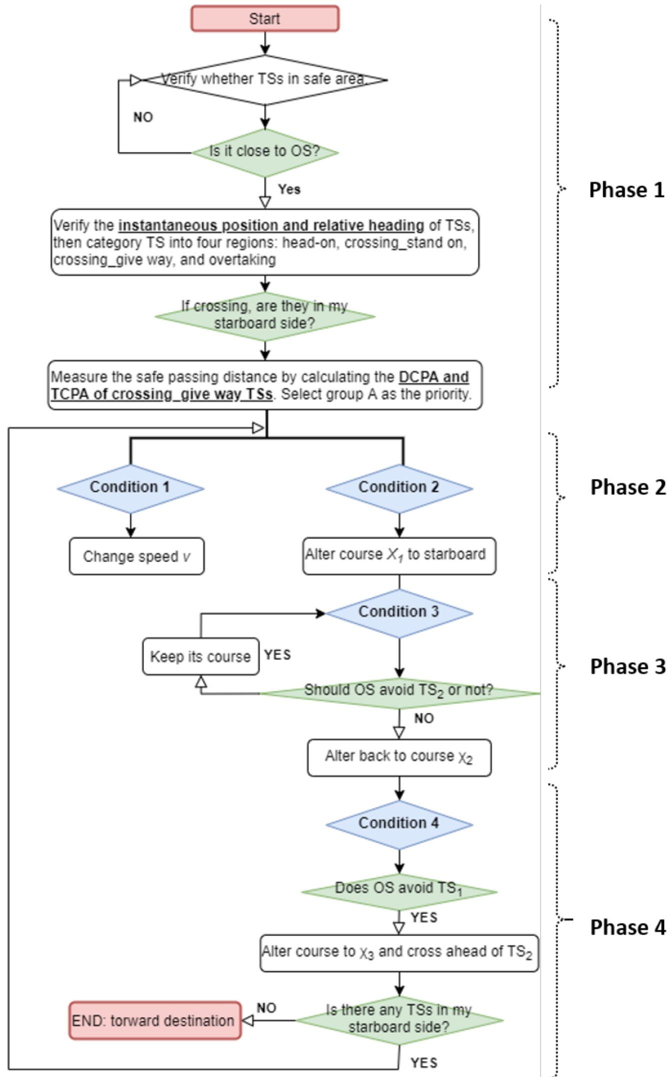

Fig. 6: Flow chart of the proposed decision making process.

Generally, the OS can't wait until all the crossing ships passed by as the schedule can not be delayed. In the third phase, before avoiding the TS1, the OS has to decide when and where to change a new course offset toward the destination. So that it is necessary to observe the changing of the DCPA and TCPA. when the CPA of group A changes to a large value, the OS can decide to come back 15° or more [9] based on the condition 3, and avoid ahead of the TS2. If the TSs in group A speed up or change its path with a high risk, the OS has to keep its course until satisfying the condition. When successfully avoiding the TS1, the OS considers whether the condition for the DCPA and TCPA are satisfied or not. Subsequently, in the fourth phase, the OS can be brought back to its predefined path and towards the destination.

C. Simulation result

Based on the proposed decision making procedure, the simulation result for a give-way vessel OS is shown in Fig. 7. It illustrates the procedure of collision avoidance with three

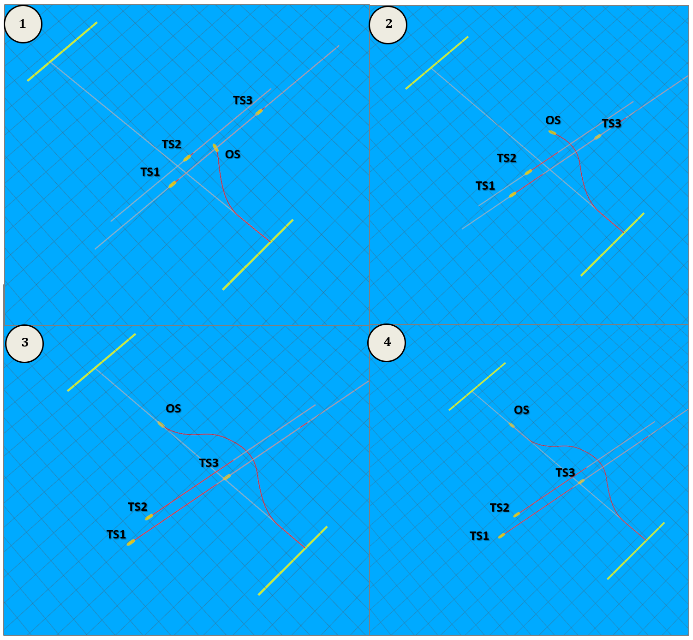

Fig. 7: Simulation result of multi-ship collision avoidance of crossing scenario.

TSs for the OS and converges to its predefined path. Three TSs are approaching to the OS's starboard side, the four ships form a crossing situation like in the Dover strait TSS area. Under this circumstance, the decision making procedure in Fig. 6 for the OS will be activated by the dangerous group. The OS alter its course to starboard and avoid among the ships successfully.

The results of the OS trajectory and its course angle during the procedure are shown in Fig. 8 with scale-down figures. The OS keeps the right angle towards the destination during the maneuvering.

V. Conclusion and Future Works

In this paper, we propose a CAS for multiple ships in close-quarters situations by integrating COLREGs rules and expert experiments into an artificial intelligent method.

Since the AIS data in the Dover strait are available, that can be obtained in the simulator in real-time. For the future work, we will compare our control strategy with real-time data. Furthermore, we will quantitatively analyze a large amount of historical data and extract more features to integrated the CAS. It will assist on-board navigational decision making and prevent the development of dangerous maritime traffic situations, in addition, it will provide for the safe and maneuvering of the ferries.

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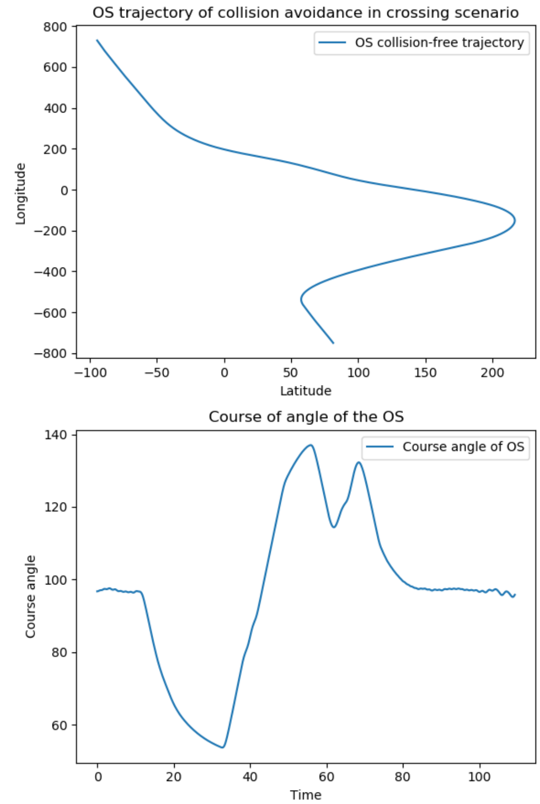

Fig. 8: Collision-free trajectory and the course angle of the OS.

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