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A rule-aware time-varying conflict risk measure for MASS considering maritime practice

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ABSTRACT

Conflict detection is a vital step of collision prevention at sea, determining if there is a risk of collision and when to take preventing actions. This article proposes a practical Rule-aware Time-varying Conflict Risk (R-TCR) for ship collision avoidance. Considering maritime practice, the conflict risk measure takes the ship maneuverability, the COLREGs, and good seamanship into account in the conflict risk measure. Specifically, the conflict risk is formulated as a ratio of achievable maneuvers leading to a collision to all achievable maneuvers. Simulations are carried out to show the characteristics of R-TCR. The results show that the R-TCR evaluates the entire conflict risk incorporating COLREG rules, multiple targets, different maneuverability, and varying ship domains. Finally, the proposed measure is applied to analyze the collision accident between two ships. Compared with the conventional risk indicators, the proposed R-TCR can deliver extra information to users, such as providing early warning, showing the room-for-maneuver, and suggesting evasive actions. Besides, the extra information also supports collision avoidance for autonomous ships.

1. Introduction

1.1. Background

Maritime transport plays an important role in the global economy while facing challenges due to frequently experienced accidents at sea. Collision is the dominant type of maritime accident. According to European Maritime Safety Agency (EMSA), collision accidents contribute to nearly 40% of accidents at sea [9]. Collisions usually cause severe consequences in loss of human life, loss of property, and environmental pollution that expose significant risk to society and individuals [31]. The severe consequences and notorious social influences have been pushing the studies on ship collision avoidance as one of the hottest topics in the maritime community [4,5].

Technically, conflict detection gives early warnings to encountering ships by evaluating collision risk. Thus, collision risk assessment is fundamental for collision avoidance [20]. In general, there are three categories of methods, namely indicator-based method (e.g., Closest Point of Approach (CPA) method, Collision Risk Index (CRI) method, etc.), ship domain-based method, probability-based method (e.g., operation space-based method, workspace-based method, etc.).

The most widely used indicators for indicator-based methods are Distance at Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA). The collision risk exists if the DCPA is less than the safe distance and the TCPA is positive; otherwise, it is null. Although the CPA method is highly unrealistic (due to its assumptions), it is widely used for the existing manned ships [44]. To make collision risk more intuitive for collision avoidance decisions, DCPA and TCPA have been combined into a CRI [1,6,11,30,37,46].

Instead of concluding a risk index, another popular group of methods is based on a concept called ship domain. The ship domain is the area around the ship that avoids the entrance of other obstacles for navigational safety [32]. The collision risk is high when 1) the Target Ship (TS) violates the ship domain of the Own Ship (OS), 2) the TS will violate the OS's ship domain shortly, or 3) the ship domains of the OS and the TS overlap.

There is also a popular method to use the probability of collision in collision risk assessment [33,38]. Additionally, the collision probability

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in operation space and workspace are both presented in existing research. The operation space-based method finds the dangerous region by collecting a set of the OS's solutions that leads to collisions [21,29,34]. The solutions refer to velocity [19] or course [43], or other operations that the OS can make to avoid a collision. Huang and van Gelder [22] proposed an innovative time-varying collision risk measure by calculating the probability of the overlap of ships' positions considering the uncertainty of maneuvers. The workspace-based method directly presents a dangerous area of one TS to the OS in the workspace to visualize collision risk [24,39,41,13]. Moreover, some methods that focus on identifying the action line surrounding the OS in geographical space have also been used for triggering evasive actions [3,27,40].

In general, indicator-based methods (CPA method and CRI method) and ship domain-based methods are usually from the perspective of two-ship encounters involving the risk of collision. In addition, they do not directly consider ship maneuverability. The probability-based method methods (e.g., operation space-based methods and workspace-based methods) can handle the problem of multi-ship encounters. Some studies have incorporated ship maneuverability using this method. However, rule-aware is not well integrated with this method in existing research. More details about collision detection techniques refer to paper [20].

The International Maritime Organization (IMO) had approved the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) since 1972 [23]. The COLREGs have been seen as the "Bible" for seamen. However, the COLREGs implicitly present some rules of action for two ships involving the risk of collision. Thus, the COLREGs require due regard to the observance of good seamanship at all times. Good seamanship is defined as a blend of professional knowledge, professional pride, and experience-based common sense for operating ships [26,18]. Good seamanship has been seen as the basis of all rules as well as the fundamental rule of the COLREGs to fill the gaps for any missing or unclear statement , [12,48,49]. Zhou et al. [47] discussed the necessity and feasibility of taking good seamanship into consideration in the application of Maritime Autonomous Surface Ships (MASS). He et al. [18] presented a collision-avoidance system with a quantitative approach for computer execution, considering the COLREGs and good seamanship. Perera et al. [35] and Perera and Guedes Soares [36] proposed decision-making processes for collision avoidances following the COLREGs. In most studies, the COLREGs are applied to conflict resolution, but they are rarely used for conflict detection, especially for risk assessment. However, some rules in the CORLEGs are related to the collision risk. For instance, Rule 7 of COLREGs contains the definition of collision risk as follows: "*(i) such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change, (ii) such risks may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.*" Due to highly subjective and ambiguous descriptions, incorporating COLREGs in conflict detection is still challenging.

1.2. Motivation

Based on the background mentioned above, there are some limitations in current collision risk research: firstly, most of the risk measures are limited to a pairwise encounter [45]; secondly, ship maneuverability is usually ignored in risk measure [21]; thirdly, COLREGs are rarely incorporated in collision risk assessment for conflict detection.

Among these limitations, we believe that the consideration of COLREGs and good seamanship is essential for collision risk measure. Good seamanship is common in marine practice. When measuring the risk, the Officers On Watch (OOW) subconsciously consider the COLREGs and good seamanship. For example, when two ships are in an encounter situation, the OOW usually choose collision avoidance actions that comply with and good seamanship. Thus, risk measures neglecting the COLREGS or good seamanship will not work in accordance with the OOW's cognition. Moreover, future waterborne transport will be mixed where both unmanned ships and manned ships exist. Thus, it would be necessary that the unmanned ships' risk measures are consistent with the manned ship to prevent possible misunderstandings.

Maneuverability is another important factor for collision risk measure. A ship usually has huge inertia and long maneuver time delay. Thus, the collision risk might be underestimated if the ship maneuverability is ignored [22].

In brief, to our best knowledge, there is no method which not only takes account of COLREG rules, good seamanship, and maneuverability but also matches risk assessment for multi-ship encounters.

1.3. Contributions

This paper proposes a practical Rule-aware Time-varying Conflict Risk (R-TCR) measure for ship collision avoidance considering COLREG rules, good seamanship, and ship maneuverability. Additionally, the proposed R-TCR is also applicable for multi-ship encounters. The conflict risk is formulated as the percentage of the achievable actions that lead to collisions. The achievable actions and the leading collision actions are identified based on ship maneuverability, COLREG rules, and good seamanship. Therefore, the proposed conflict risk represents the difficulty for the OS to avoid collisions.

The R-TCR is proposed based on the measure presented in (Huang et al., 2019), and the main contributions of this paper are concluded as follows:

1) COLREG rules and good seamanship are considered in risk measures. Specifically, Rules 7, 8, 11, 13, 14, 15, 16, 17 of COLREG rules are incorporated.
2) The R-TCR is defined as a percentage of the achievable actions that lead to conflict considering ship maneuverability, which helps the ship detecting conflicts and finding solutions.
3) The R-TCR could apply to the multi-ship encounter situation, which is essential for collision avoidance systems for MASS.

The MASS in this paper is defined as a ship that, to a varying degree, can operate independently of human interaction. MASS have different Degrees of Autonomy (DoA), including ship with automated processes and decision support; remotely controlled ship with seafarers on board; remotely controlled ship without seafarers on board; and fully autonomous ship.

The outline of this paper is described as follows: Section 2 provides the definition, assumptions, and the framework of the proposed R-TCR; Section 3 investigates the performance of the R-TCR in various encounter scenarios, followed by an analysis of a real collision accident in Section 4; Subsequently, the advantages and the limitations of the R-TCR are discussed in Section 5; In the end, the findings and future work are concluded in Section 6.

2. Methodology

This section addresses the methodology of the proposed rule-aware time-varying conflict risk (R-TCR) measure model, considering the maneuverability of the OS, COLREG rules, and good seamanship. We firstly provide the definitions and assumptions. Then, the framework of the R-TCR measure is proposed.

2.1. Definitions and assumptions

Risk takes on many forms in existing research. A widely accepted form is the likelihood of danger (loss) together with an indication of how serious that danger (loss) could be [2]. For collision prevention purposes, most studies focused on the likelihood of the collision [14,28].

Collision is usually defined as a contact of ships. However, in practice, it is unacceptable for an OOW when the OS's domain is violated.

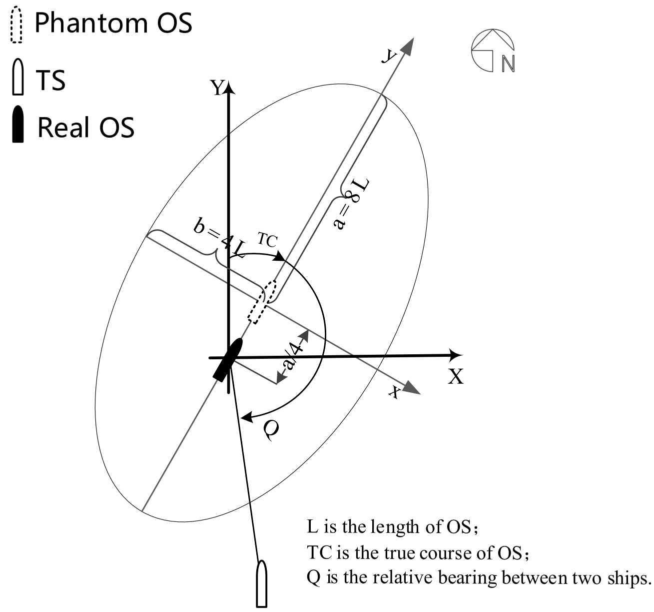

Fig. 1. Demonstration of the coordinate system and ship domain (overtaking situation).

Therefore, the concept of conflict risk is introduced in this paper, which is the probability of the violation of the ship domain.

Definition 1. Conflict refers to the event that a TS violates the OS's ship domain.

Definition 2. Conflict risk is the probability of the violation of the ship domain.

The conflict risk is formulated as the percentage of the achievable actions that lead to conflict (Eq. 1), which is called TCR (Time-varying Conflict Risk):

$$\mathrm{TCR} = \frac{\sum_{i=1}^{k} p(\mathit{dangerous}\ \mathrm{action}(i))}{\sum_{i=1}^{n} p(\mathit{achievable}\ \mathrm{action}(i))}, \tag{1}$$

where $p(\mathit{dangerous}\ \mathrm{action}(i))$ is the probability of choosing dangerous action(i); $p(\mathit{achievable}\ \mathrm{action}(i))$ is the probability of achievable action (i); k and n is the total number of dangerous and achievable actions, respectively.

To make out the accurate number of dangerous or achievable actions, we consider the rules of the COLREGs and made further assumptions.

Assumption 1. The action only refers to the alteration of course.

According to Rule 8 of the COLREGs, under most circumstances, the alteration is the most effective action to avoid a close-quarters situation, especially at the open sea when ample sea room is available.

Assumption 2. Power-driven ships in sight of one another are sailing at open and calm sea under good visibility.

Assumption 3. The probability of action choices yields is a uniform distribution.

Then, the TCR is modified to the Rule-aware TCR (R-TCR) as followed:

$$\text{R-TCR} = \frac{n(DA)}{n(AA)}, \tag{2}$$

where $n(AA)$ is the number of achievable actions; $n(DA)$ is the number of dangerous actions.

Definition 3. Achievable action (AA) is a set of courses that the OS can reach at the current juncture, considering the COLREGs.

Definition 4. Dangerous action (DA) is a subset of AA that includes courses of the OS that could lead to conflict between the OS and TSs.

2.2. *The framework of R-TCR measure*

The key for R-TCR measure is constructing AA and DA, considering the maneuverability and COLREG rules. The details are concluded in the following sub-sections.

2.2.1. *Rule-aware achievable actions*

In principle, the OS could alter arbitrary courses if COLREG rules and good seamanship are ignored. However, according to the OOWs' preferences and the limitations of the rudder, the range of course changes usually would not be larger than 90 deg [32]. Moreover, different encounters might lead to diverse rule-aware achievable course range. The rule-aware achievable course ranges for head-on, crossing, and overtaking situation are [0°, 90°, 0°, 90°] and [−90°, 90°], respectively. A positive value represents an altering course to starboard, and a negative value represents an altering course to the port side.

For ships in the head-on situation, Rule 14 of COLREGs states: "When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other". Accordingly, ships passing from portside to portside can realize collision avoidance. Therefore, the achievable course range for the head-on situation is [0°,90°].

For ships in a crossing situation, Rule 15 of COLREGs states: "When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel. " According to this rule, if there is a target ship on the starboard side of the OS, altering course to the starboard side is a rule-compliant evasive action to avoid crossing ahead of the target ship when conditions permit. Therefore, the achievable course range for the crossing situation is [0°,90°].

For ships in an overtaking situation, Rule 13 of COLREGs states: "Notwithstanding anything contained in the Rules of this Section any vessel overtaking any other shall keep out of the way of the vessel being overtaken." Accordingly, the ship can turn portside or starboard to avoid the collision. Thus, the achievable course range for the overtaking situation is [−90°,90°].

2.2.2. *Dangerous actions incorporating manoeuvrability and COLREG rule*

(1) Rule-aware ship domains

Fujii and Tanaka [10] originally proposed the elliptical ship domain with the OS ship in the center. However, Goodwin [15,16] observed the influence of COLREGs and developed a new ship domain with an integration of 3 different sectors. Davis et al. [7] smoothed the integrations with a circle boundary and set a "phantom ship" in the center for easy expression in math. Phantom ship is the center of the ship domain, not the real ship. The actual center of the ship is located astern of the phantom ship's portside. The real ship is fixed by a distance and an angle (relative to the ship's head) from the phantom ship. Distances can be directly compared from the phantom ship between the domain size and the distance to the target ship. Hence, the phantom ship provides convenience for judging whether the domain is infringed by target ships, see Fig. 1.

By referencing the previous research [17,18], different ship domain models are selected for different encountered situations as shown in Fig. 2, specific parameters of ship domain in Table 1. Fig. 1 shows the ship domain in an overtaking situation.

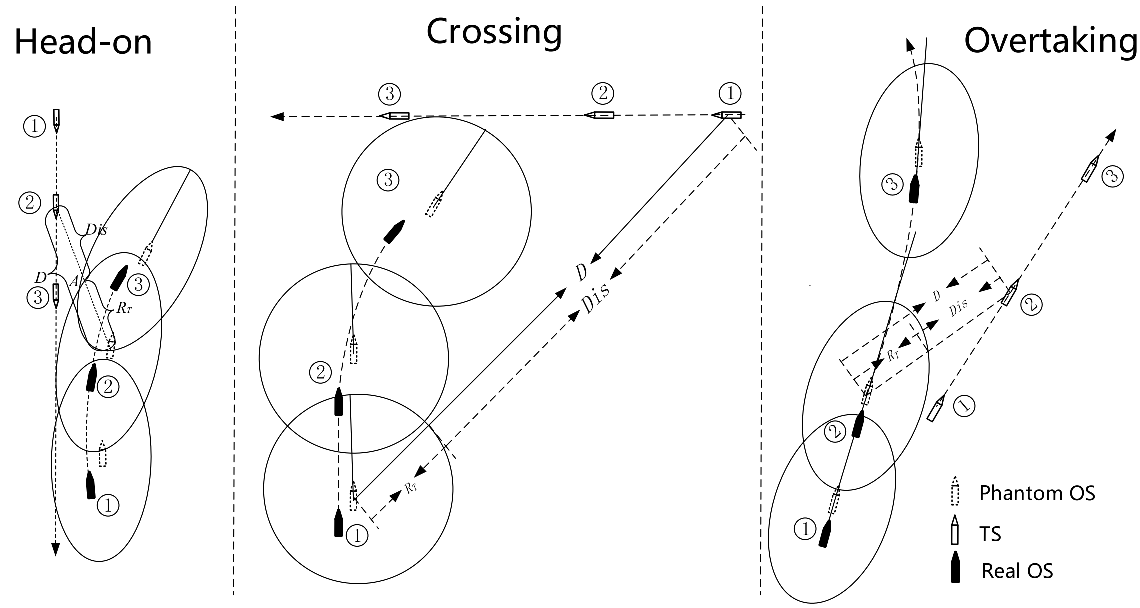

Fig. 2. Process of the OS altering course to avoid collisions.

Table 1
Ship domain parameters.

Encounter situation	Scale	Shape	Explanation
Head-on	$a = 8$ L, $b = 4$L	Ellipse	a and b are the lengths of semi-major and semi-minor axes of the ellipse
Overtaking	$a = 5$ L, $b = 4$L		
Crossing	$R = 4$L	Circle	R is the radius of the circle.

* L is the OS's length, and the ship domain scale can refer to paper [18].

Head-on situation accepts an elliptical ship domain. According to Rule 14 of COLREGs, ships passing from portside to portside can realize collision avoidance. It implies that the space of the ship domain on the port side of the ship is larger than that on the starboard side. Besides, since two ships are approaching each other from the bow, the space of domain in the front of the ship is larger than that in the back of the ship.

The crossing situation uses a circular ship domain, while the ship is not at the center of the circle. Unlike the head-on situation, the TSs mainly approach the OS from the OS's port or starboard side. Thus, the space of domain in the bow/stern of the ship would not be larger than that in the port/starboard side of the ship. Thereby, a circular ship domain is selected. Additionally, according to Rule 15 of COLREGs, the OS should alter course to the starboard side to avoid the TS approaching from her starboard side. It implies that the space of domain on the starboard side of the ship would be larger than that on the port side. In brief, the ship domain proposed by [7] is adopted here.

Overtaking situation employs an elliptical domain. According to Rule 13 of COLREGs, the ship can turn portside or starboard to avoid collisions. Thus, the port and starboard side of the ship domain would be equal, while the bow side of the domain is larger than the stern side. Moreover, the ship domain parameters are not fixed all the time. The parameters can be further adjusted by the captain [18].

(1) **The relative distance between ships considering rule-aware ship domains and ship maneuverability**

According to Definition 2, conflict risk is the probability of the violation of the ship domain. Hence, the distance between TS and OS's domain boundary is an important index for judging whether the TS invades the OS's domain or not.

Fig. 2 shows the processes of the OS chooses its courses under different encounter situations. D is the distance between the phantom ship and the TS; Dis represents the distance between the TS and the OS's domain boundary; R_T is the distance between the phantom ship and the OS's domain boundary. Dis, D, and R_T are on the same line, and the relationship among them is shown in Eq. (3).

$$D = Dis + R_T, \tag{3}$$

Obviously, Dis, D, and R_T change over time. The formula of Dis at different times is shown as follows:

$$Dis^{(i)} = D^{(i)} - {R_T}^{(i)}, \tag{4}$$

where $D^{(i)}$ is the distance between the center of the OS's domain and the TS at i time; $Dis^{(i)}$ is the distance between the TS and the OS's domain boundary at i time; $R_T^{(i)}$ is the distance between the center and the boundary of the OS's domain. $D^{(i)}$ and $R_T^{(i)}$ are calculated via Eq.(5) and Eq.(6):

$$D^{(i)} = \sqrt{\left({X_R}^{(i)} - {X_{01}}^{(i)}\right)^2 + \left({Y_R}^{(i)} - {Y_{01}}^{(i)}\right)^2} \tag{5}$$

where $({X_R}^{(i)}, {Y_R}^{(i)})$ is the TS's position coordinate; $({X_{01}}^{(i)}, {Y_{01}}^{(i)})$ is the phantom ship's position coordinate.

$${R_T}^{(i)} = \frac{a\cdot b}{\sqrt{\left(a\cdot \sin Q^{(i)}\right)^2 + \left(b\cdot \cos Q^{(i)}\right)^2}} \tag{6}$$

where a and b are the lengths of the semi-major and semi-minor axes of the ellipse, respectively; $R_T^{(i)}$ is relative bearing between TS and phantom ship at i time. $Q^{(i)}$ is calculated via Eq.(7):

$$Q^{(i)} = \begin{cases} \arcsin\left(\dfrac{\left({X_R}^{(i)} - {X_{01}}^{(i)}\right)}{D^{(i)}}\right) - C_0, & {Y_R}^{(i)} - {Y_{01}}^{(i)} < 0 \\ \pi - \arcsin\left(\dfrac{\left({X_R}^{(i)} - {X_{01}}^{(i)}\right)}{D^{(i)}}\right) - C_0, & {Y_R}^{(i)} - {Y_{01}}^{(i)} \geq 0 \end{cases} \tag{7}$$

According to different encountering situations, the phantom ship's position coordinate $({X_{01}}^{(i)}, {Y_{01}}^{(i)})$ is calculated as follows:

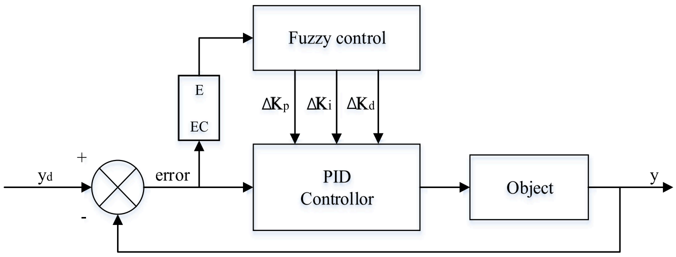

Fig. 3. The principle of fuzzy adaptive PID control.

Table 2
Parameters in simulation.

Parameter	Value	Parameter	Value
Name	HUAYANG DREAM	Displacement (kg)	$90,000 \times 10^3$
Draft (m)	14.5	Breadth (m)	32.5
LOA (m)	225	Density of water (kg/m^3)	1000
Block coefficient	0.8715	RPM (r/min)	90
Area of rudder (m^2)	56.88	Propeller advance (m)	4.738

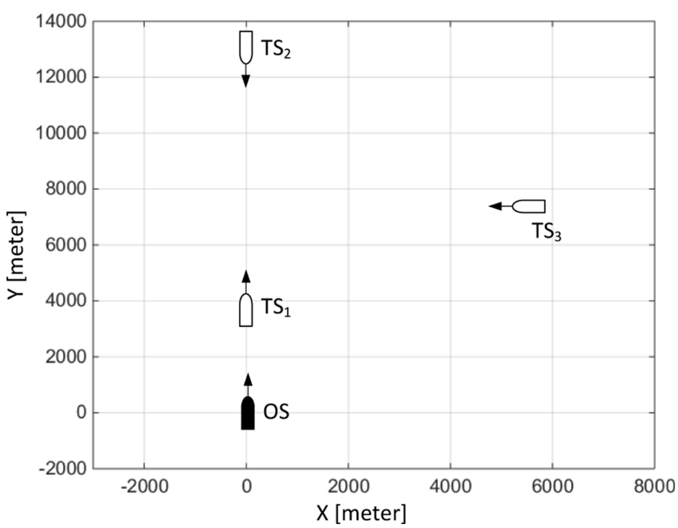

Fig. 4. Planar layout of the ships (Scenario1).

$$\text{head}-\text{on situation}:\begin{cases}X_{01}{}^{(i)}=X_0{}^{(i)}+\sin\left(C_0+19^0\right)\times\frac{Rd}{4}\\ Y_{01}{}^{(i)}=Y_0{}^{(i)}+\cos\left(C_0+19^0\right)\times\frac{Rd}{4}\end{cases}$$

$$\text{crossing situation}:\begin{cases}X_{01}{}^{(i)}=X_0{}^{(i)}+\sin\left(C_0+19^0\right)\times\frac{R}{2}\\ Y_{01}{}^{(i)}=Y_0{}^{(i)}+\cos\left(C_0+19^0\right)\times\frac{R}{2}\end{cases} \tag{8}$$

$$\text{overtaking situation}:\begin{cases}X_{01}{}^{(i)}=X_0{}^{(i)}+\sin C_0\times\frac{a}{4}\\ Y_{01}{}^{(i)}=Y_0{}^{(i)}+\cos C_0\times\frac{a}{4}\end{cases}$$

where $(X_0{}^{(i)}, Y_0{}^{(i)})$ is the position of the OS; R_d is the distance (R_T) between phantom ship and the OS's domain boundary when $Q^{(i)}$ is 19 °; R is the radius of the circular ship domain.

The position of the TS $(X_R{}^{(i)}, Y_R{}^{(i)})$ is calculated as follows:

$$\begin{cases}X_R{}^{(i)} = X_R{}^{(0)} + v_1 \times \sin C_1 \times i\\ Y_R{}^{(i)} = Y_R{}^{(0)} + v_1 \times \cos C_1 \times i\end{cases} \tag{9}$$

where $(X_R{}^{(0)}, Y_R{}^{(0)})$ is the initial position; v_1 and C_1 are the speed and the heading of the TS.

The position of the OS, i.e., $(X_0{}^{(i)}, Y_0{}^{(i)})$, is calculated by using the mathematical Model Group (MMG) model [42]. A 3 Degree of Freedom (DoF) MMG model is presented as follows:

$$\begin{cases}(m+m_x)\dot{u}-\left(m+m_y\right)vr = X_H+X_P+X_R\\ \left(m+m_y\right)\dot{v}-(m+m_x)ur = Y_H+Y_P+Y_R\\ \quad (I_{ZZ}+J_{ZZ})\dot{r} = N_H+N_R+N_R\end{cases}, \tag{10}$$

where m, m_x, m_y, I_{ZZ} and J_{ZZ} are ship quality, added mass, inertia moment, and additional inertia moment, respectively; Subscript *H, P, R* are bare hull, propeller, rudder, respectively; *u, v, r* are the ship longitudinal, transverse components of the velocity vector and the steering angle velocity, respectively; *X, Y, N* are the external forces and moments in different directions, respectively. More information refers to [32].

The autopilot system is popular in modern ships. When the course is set, the autopilot system can automatically control the rudder command to achieve the set course. The fuzzy adaptive Proportion Integral Derivative (PID) control model is used to simulate the process of ship motion control. The fuzzy adaptive PID control principle is shown in Fig. 3. The fuzzy rules adopted in this paper are from paper [18].

(1) **Calculation of DA based on the relative distance between ships**

Combining Eq. (3)-(10), the value of the relative distance between ships (*Dis*) at any time can be obtained. *Dis* has the following characteristics:

① Along with the two ships approaching, the value of *Dis* decreases.
② When the condition $Dis^{(i+1)} > Dis^{(i)}$ is satisfied for the first time, the OS has passed the CPA.
③ When $Dis^{(i)} < 0$, it means that the TS enters the OS' ship domain.
④ When $Dis^{(i)} > 0$, it means that the TS passes outside the OS' ship domain.

Therefore, if $Dis^{(i+1)} > Dis^{(i)} > 0$ is satisfied for the first time, it means that the existing course of the OS would not lead to conflict with the TS. If we collect all the possible altering courses causing conflict in a set called DA set, then the margin of the DA set is an altering course that would lead to the trajectory of the TS tangent to the domain of the OS. This course is denoted as TC_2^k. Thus, if the altering course value is greater than the TC_2^k, the TS's trajectory will be outside the OS' ship domain, i.e., the TS will not violate the OS's ship domain; if the altering course is less than TC_2^k, the TS will violate the OS's ship domain. A negative value of TC_2^k means that the ship turns port side and a positive value means that the ship turns to the starboard side. When TC_2^k is positive, it is denoted as pTC_2^k that means positive TC_2^k; when TC_2^k is negative, it is denoted in nTC_2^k. Therefore, we can formulate the DA set as: $[0,pTC_2^k]$ or $[nTC_2^k, 0]$, or $[nTC_2^k,pTC_2^k]$.

Accordingly, pTC_2^k can be calculated with the algorithm shown in Algorithm 1, while nTC_2^k is calculated by Algorithm 2.

2.2.3. Calculation of R-TCR

According to the definition in Section 2.1, the calculation of R-TCR is shown in Eq. (2), i.e., R-TCR equals the ratio of the number of Dangerous Actions to the number of Achievable Actions.

3. Characteristics of R-TCR

To investigate the characteristics of R-TCR, we carried out a series of simulations of different encounters. The factors influencing R-TCR are investigated, and the characteristics of R-TCR are analyzed by

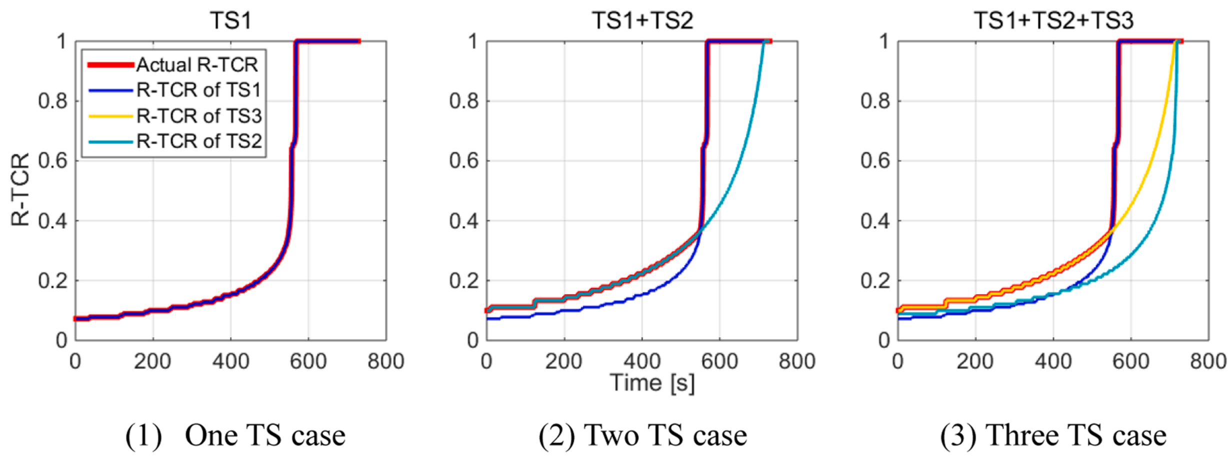

Fig. 5. The result of multiple encounters.

Table 3
Scenario1: Initial State of Ships.

Ship	Coordinates (X, Y) (NM)	Speed (knots)	Course ( )	Length (m)	DCPA (NM)	TCPA (s)
OS	(0,0)	15.6	000	225	–	–
TS_1	(0,2)	7.8	000	180	0	926
TS_2	(3,4)	11.7	270	180	0	926
TS_3	(0,7)	11.7	180	180	0	926

comparisons with other methods (e.g., CRI and the original TCR).

3.1. Set up

The OS is set as an unmanned ship whose dynamics are described by a 3 DoF MMG model of a Panamax bulk carrier, called MV HUAYANG DREAM. Besides, the fuzzy adaptive PID controller is applied to control the OS's behavior, and other ships are assumed to be manned ships. The related parameters are shown in Table 2.

3.2. Influence of the number of TSs

In this scenario, we carry out 3 cases that increase the number of TSs:

- One TS case: TS_1 and the OS form an overtaking situation.
- Two TS case: TS_1 and the OS form an overtaking situation;

  TS_2 and the OS form a crossing situation.

- Three TS case: TS_1 and the OS form an overtaking situation;

  TS_2 and the OS form a crossing situation;
  TS_3 and the OS form a head-on situation.

The spatial layout of the four ships is shown in Fig. 4. The OS is placed at the origin, heading to the North with a speed of 15.6 knots. The initial values of DCPA and TCPA between the OS and TS in each case are equal, DCPA=0 NM, TCPA=926 s.

Firstly, OS encounters TS_1 whose TCPA and DCPA are 926 s and 0 NM in an overtaking situation. In this case, TS_1 approaches OS from the stern. As shown in Fig. 5(1), the R-TCR increases with time. At 0 s, the R-TCR is 0.072, i.e., the probability that collision can not be avoided by only changing the OS's course is 0.072. At 568 s, the R-TCR reaches 1, which means the probability of preventing collision by changing the OS's course is 0.

Secondly, one more ship (TS_2) is added. TS_2 approaches OS from the bow of OS. In Fig. 5(2), we can observe that the R-TCR increases with the number of TSs during 0–549 s. Specifically, the value of R-TCR raises from 0.1 to 0.13. The increase of R-TCR means that the situation becomes more dangerous than the situation in the one TS case. However, after 549 s, the influence of the added TS_2 fades away. At 560 s, R-TCR=0.65, which is the same as R-TCR in the one TS case.

Thirdly, TS_3 is added, i.e., four ships encounter in the case. TS_3 approaches OS from the starboard of OS, forming the crossing situation. According to Fig. 5(3), the R-TCR value does not increase when TS_3 is added. That is to say, R-TCR does not always increase with the number of TSs. It depends on whether the additional ships change the ship's maneuvering space.

3.3. Influence of the maneuverability of the OS

Three types of encountering situations are simulated in this part, i.e., head-on, crossing, and overtaking. In each situation, conflict risk in two cases is analyzed:

(1) With maneuverability: the actual maneuverability of the OS is considered;
(2) Without maneuverability: the maneuverability is ignored in the risk assessment, i.e., it presumes that the course can change immediately.

The initial setting of the ships is shown in Table 3. The initial values of DCPA and TCPA between two ships in this experiment are equal, i.e., DCPA=0 NM and TCPA=926 s.

The R-TCR values in the head-on, crossing, and overtaking situations are shown in Fig. 6. The difference between R-TCR with and without maneuverability is slight at first. However, over time, the striking disparity between the two cases arises. It shows that the R-TCR values considering the OS maneuverability are higher than that ignoring the maneuverability. It implies that the R-TCR value is underestimated when the maneuverability is ignored.

Since the ships are designed to collide with each other, the R-TCR values will all reach 1 in the end. However, we can observe the different manners of the increase of the R-TCR values. The conflict risk is small and increases slowly in the first 400 s, while it dramatically increase after 400 s as time goes by. It implies that the ship should take early action, which is also compliant with the COLREGs.

3.4. Comparing with CRI method

In this part, we compare the proposed R-TCR with the traditional CRI method. The traditional CRI combines DCPA and TCPA by the weighted method [25], see Eq. (11). For this reason, three typical encounter scenes are set for the experiment, and the settings of ships are shown in Table 3. The parameters of the CRI method are set as follows: $\alpha_1 = 1$ and $\alpha_2 = 2$.

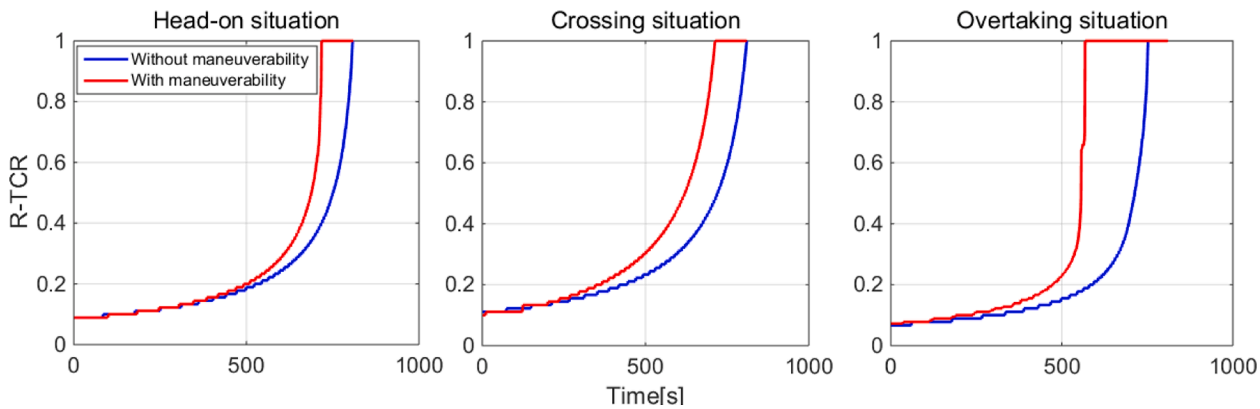

Fig. 6. Time-varying R-TCR.

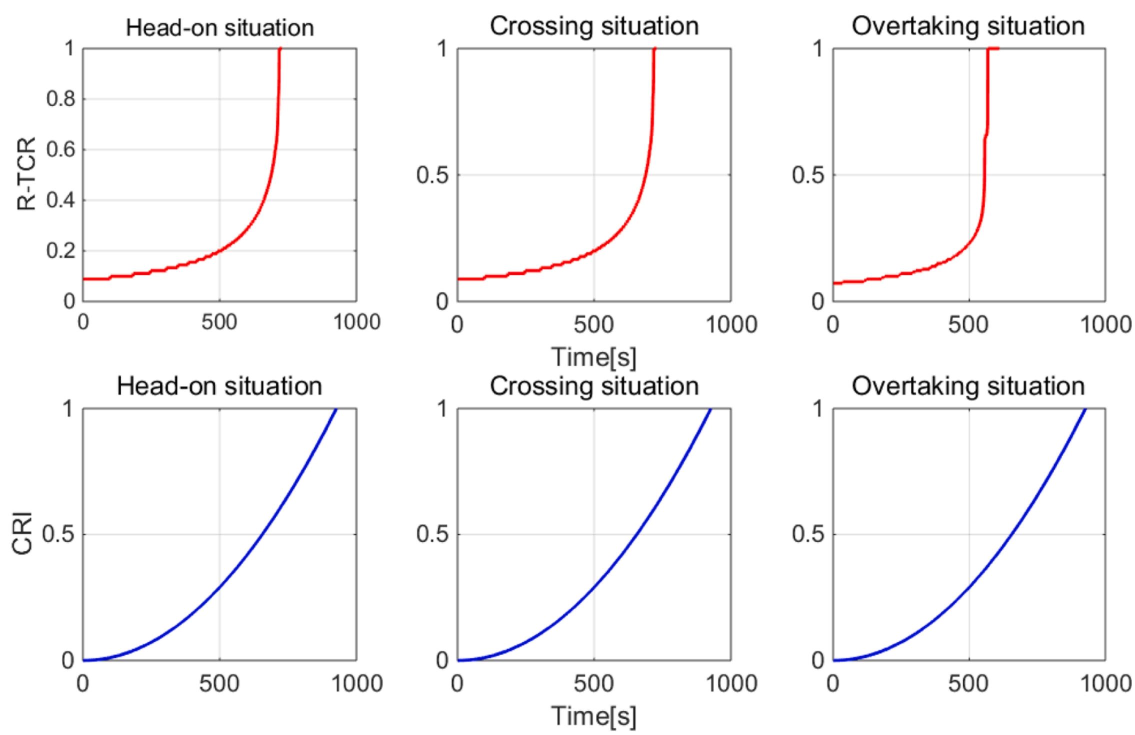

Fig. 7. The difference between R-TCR and CRI method.

Table 4
Settings of experiment.

Method	Achievable action [°]	Ship domain	Encounter situation
TCR	[−180,180]	Circle ship domain with a radius of 4L	Head-on
	[−180,180]		Crossing
	[−180,180]		Overtaking
R-TCR	[0,90]	Eccentric ship domain, see Table 1	Head-on
	[0,90]		Crossing
	[−90,90]		Overtaking

$$\mathrm{CRI}^{(t)} = \alpha_1 \times \left(\frac{Max(TCPA^{(t)}) - TCPA^{(t)}}{Max(TCPA^{(t)})}\right)^2 + \alpha_2 \times \left(DCPA^{(t)}\right)^2 \quad (11)$$

where $DCPA^{(t)}$ is the distance at the closest point of approach at t time; $(TCPA^{(t)})$ is the time to the closest point of approach at t time.

The values of R-TCR and CRI in different encounter situations are shown in Fig. 7. No matter which methods are used, the trend of CRI or R-TCR is the same, i.e., increases with time. However, the two methods have three differences. Firstly, the CRI values in the three encounters are the same since the DCPA and TCPA are the same in these encounters, while the R-TCR values are different. It implies that the CRI method is not suitable for finding out the most dangerous ships in some multi-ship encounter situations, while the R-TCR method can. Secondly, the CRI method combines DCPA and TCPA that are not dimensional values. As a result, the CRI has no physical significance. On the contrary, the R-TCR can represent the probability of collision that the ship can not avoid the dangers, which indicates the difficulty to avoid collisions. Finally, when the R-TCR reaches 1, it means that the ship is impossible to make the TS pass the OS at a safe distance just by one ship taking avoidance action. However, at this time, the CRI did not reach 1, which was inconsistent with the OOW's estimation of the risk. CRI arrives at 1 later than R-TCR, which also implies that the CRI method might underestimate the risk. In brief, the R-TCR method can be applied to multi-ship encounters, has physical significance, and is more suitable for triggering evasive actions than CRI methods in some cases.

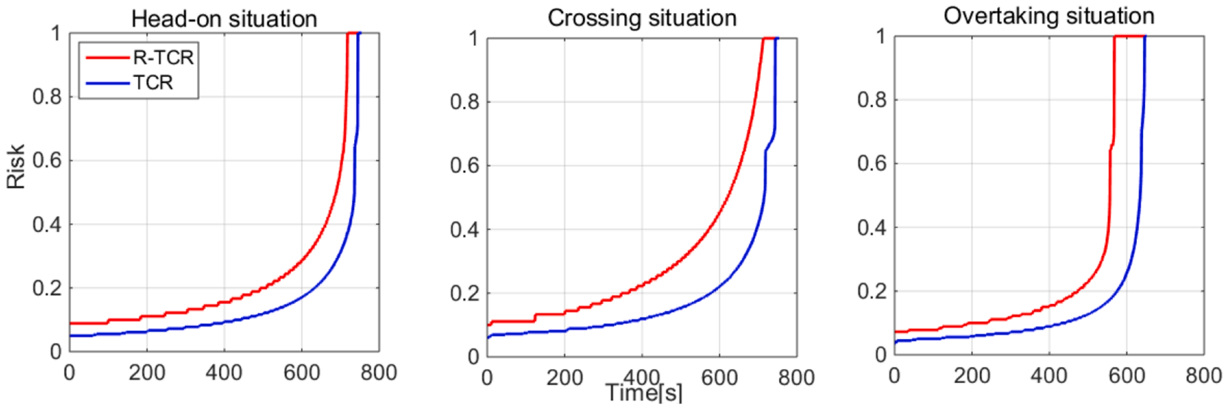

Fig. 8. The difference between R-TCR and TCR method.

Table 5
Parameters of Sanchi and CF Crystal.

Vessel Details	SANCHI	CF CRYSTAL
Flag	Panama	Hong Kong (China)
Call Sign	3FJU8	VRIC2
IMO Number	9,356,608	9,497,050
Vessel Type	Oil Tanker	Bulk Carrier
Material of Hul	Steel	Steel
Gross Tonnage	85,462	41,073
Net Tonnage	53,441	25,634
Length Overall (m)	274.18	225
Beam (m)	50.04	32.26
Depth (m)	23.1	19.60
Summer Deadweight (t)	164,160	75,725.19
Engine Power (kW)	16,794	8833

*The turning cycles of two ships have been simulated in the appendix.

Algorithm 1
Calculation of pTC_2^k.

Step 1. Initial condition setting: MMG model parameter setting, fuzzy PID control model parameter, the OS domain, initial heading, speed, position, and other data of the OS and the TS.
Step 2. Set the initial values required for some algorithm loops, such as initial alter course TC_2=0, time step $\Delta t = 1$, initial time $k = 0$, computing time $i = 0$.
Step 3. If $TC_2 \le 90$, calculate the position of the OS and TSs at time i, go to the next step; otherwise, end the algorithm.
Step 4. If $Dis^{(i)} < 0$, or $Dis^{(i-1)} < 0$, $TC_2 = TC_2 + 1$, go to step 3; otherwise, go to the next step.
Step 5. If $Dis^{(i+1)} > Dis^{(i)}$, $pTC_2^k = TC_2$; otherwise, $i = i + 1$, go to step 3.
Step 6. If $k \le$ TCPA, $k = k + 1$, calculate the position of the OS and TSs at time k, go to step 2; otherwise, end the algorithm.

Algorithm 2
Calculation of nTC_2^k.

Step 1. Initial condition setting: MMG model parameter setting, fuzzy PID control model parameter, the OS's domain, initial heading, speed, position, and other data of the OS and the TS.
Step 2. Set the initial values required for some algorithm loops, such as initial alter course TC_2=0, time step $\Delta t = 1$, initial time $k = 0$, computing time $i = 0$.
Step 3. If $TC_2 \ge -90$, calculate the position of the OS and TSs at time i, go to the next step; otherwise, end the algorithm.
Step 4. If $Dis^{(i)} < 0$, or $Dis^{(i-1)} < 0$, $TC_2 = TC_2 - 1$, go to step 3; otherwise, go to the next step.
Step 5. If $Dis^{(i+1)} > Dis^{(i)}$, $nTC_2^k = TC_2$; otherwise, $i = i + 1$, go to step 3.
Step 6. If $k \le$ TCPA, $k = k + 1$, calculate the position of the OS and TSs at time k, go to step 2; otherwise, end the algorithm.

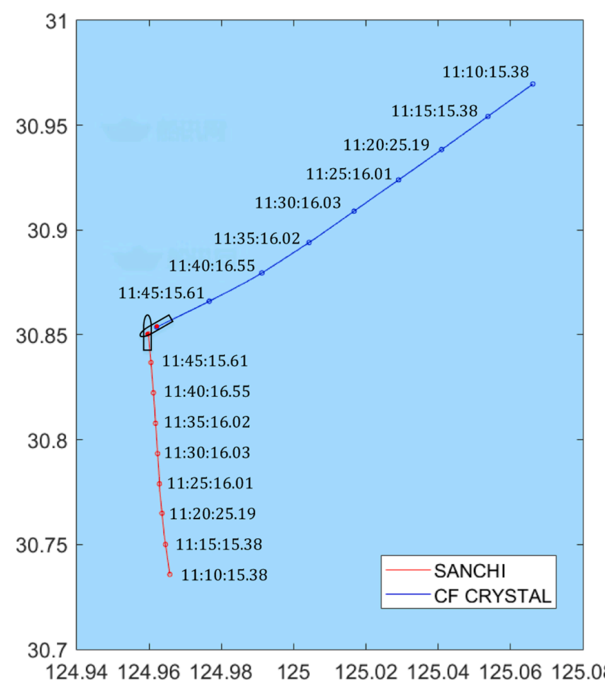

Fig. 9. Trajectories of the two ships.

3.5. Comparing with original TCR method

This section compares the differences between the proposed R-TCR method and the TCR method. The difference between the R-TCR method and the TCR method lies in whether the COLREGs are considered. The specific differences are concluded in Table 4. The proposed R-TCR method narrows down the range of achievable actions and selects different ship domains. To compare the performance of these methods, three typical encounter situations are set up, and the settings of the ships are presented in Table 3.

Simulation results are shown in Fig. 8. From the results, we observe that the value of R-TCR is not smaller than TCR. The reason is that the number of dangerous actions is the same, but rules limit the range of achievable actions considered by the R-TCR. From the perspective of rules, the directions of achievable actions should be limited. Additionally, from the perspective of good seamanship, the range of achievable actions should also be limited. For example, in a head-on situation, the ship should not turn to the portside. Thus, if TCR is used to evaluate the conflict risk, it is not in line with the OOW's cognition.

Moreover, we observe that the R-TCR reaches 1 earlier than the TCR. The main reason is the difference in ship domains. The TCR adopts a unified ship domain, and the R-TCR determines the ship domain

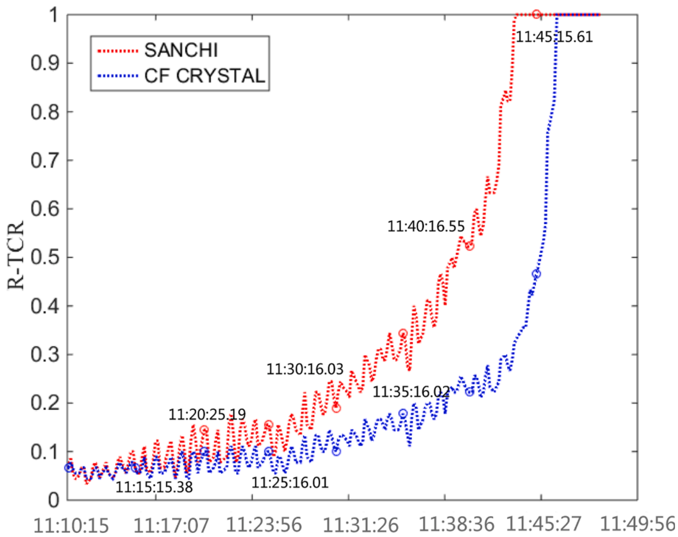

Fig. 10. R-TCR of the two ships.

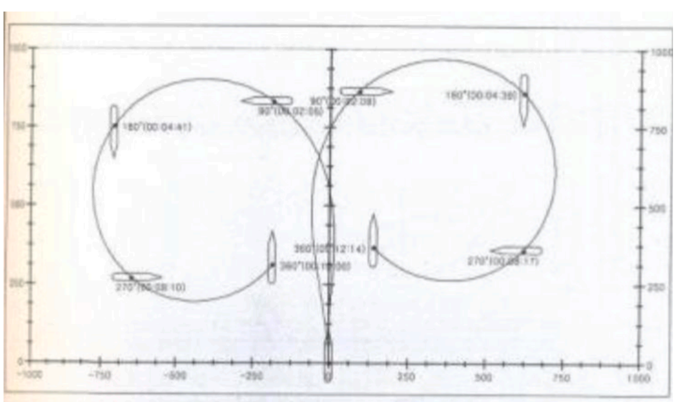

Fig. 11. A. Real ship model turning cycle of SANCHI Oil Tanker from accident report.

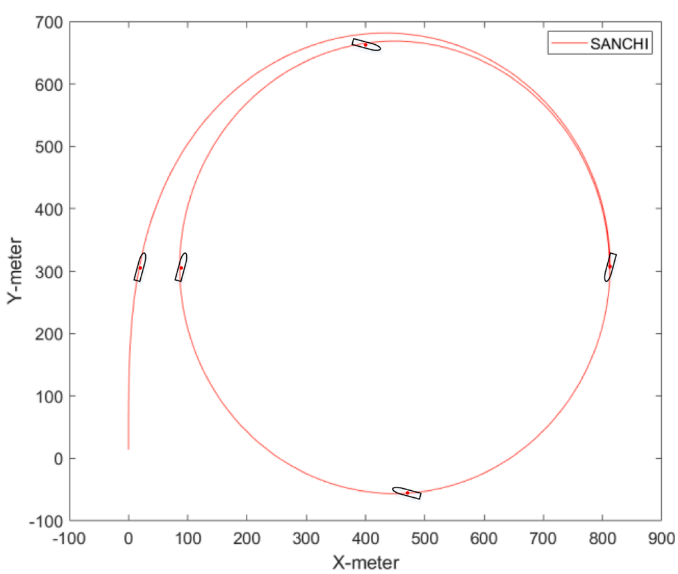

Fig. 12. A. Digital MMG model turning cycle (SANCHI).

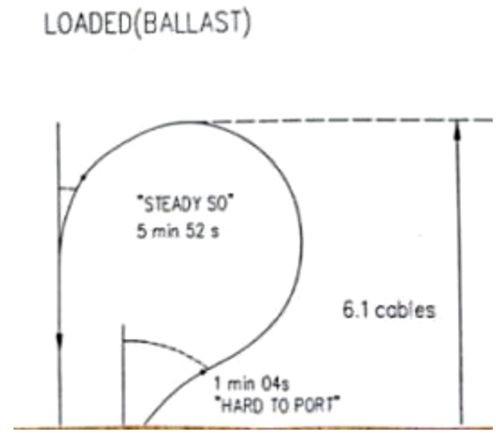

Fig. 13. A. The overboard rescue manoeuver trajectory of CF CRYSTAL from accident report.

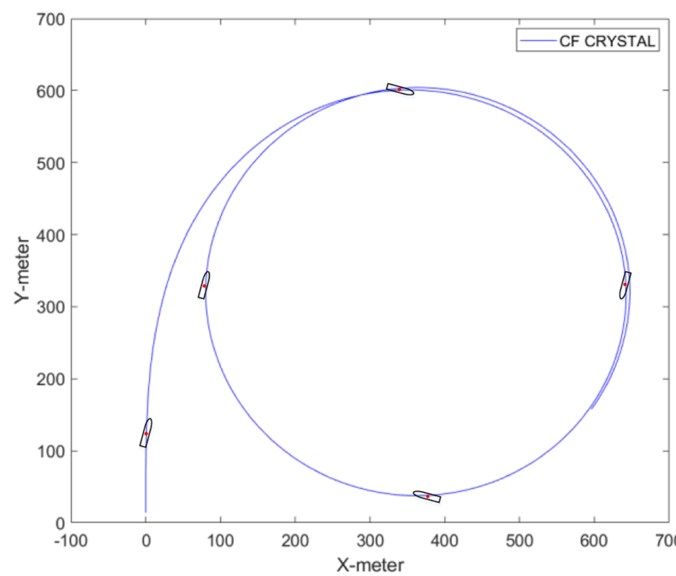

Fig. 14. A. Digital MMG model turning cycle (CF CRYSTAL).

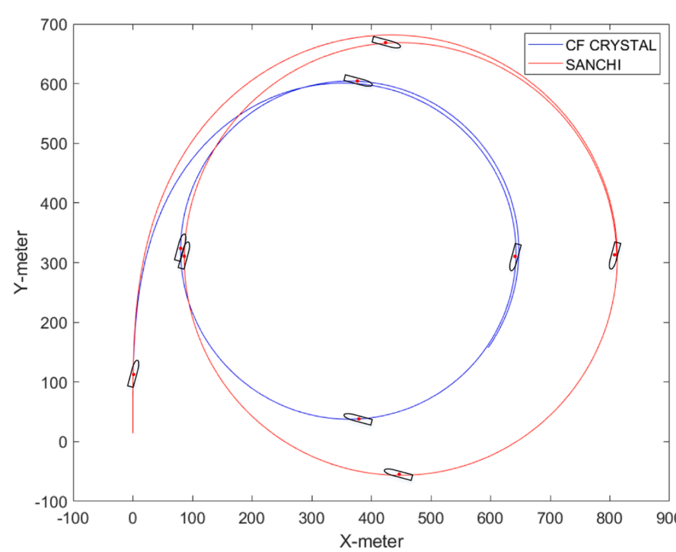

Fig. 15. A. Digital MMG model turning cycles (CF CRYSTAL and SANCHI).

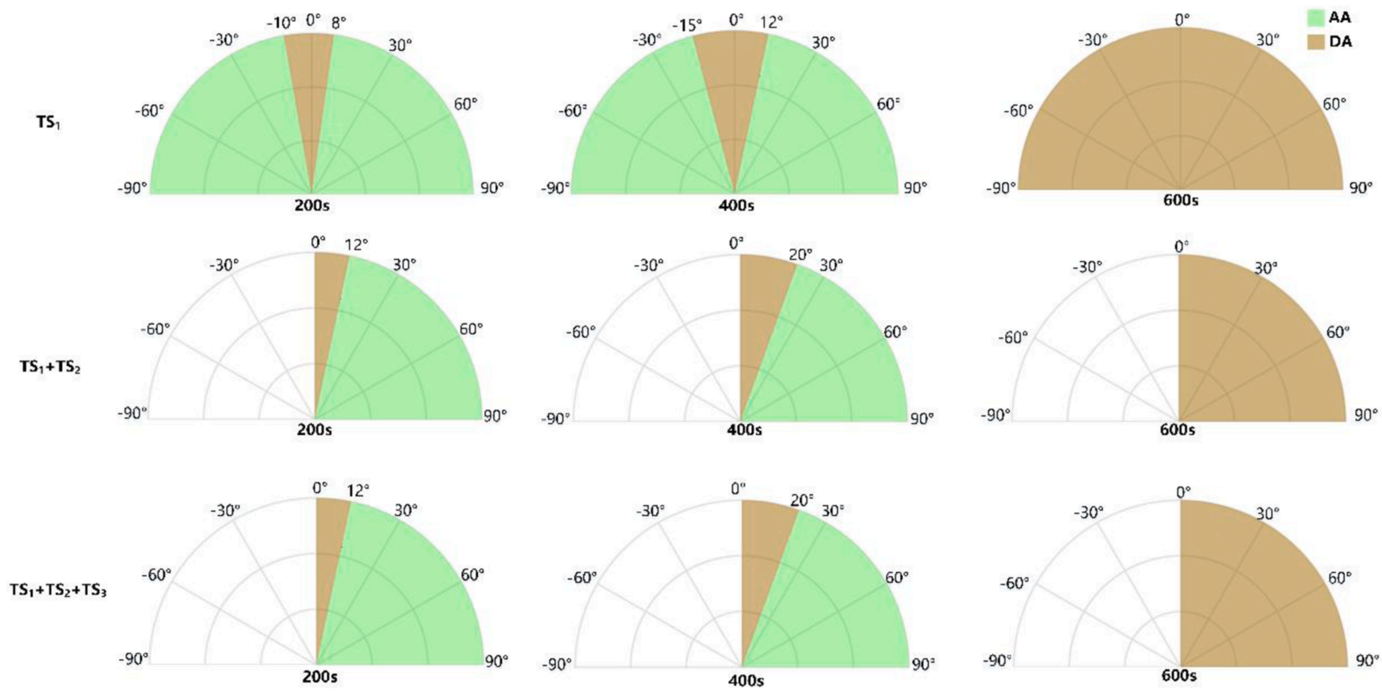

Fig. 16. B. The maneuvering space of the OS encounters multiple ships at different moments (200 [s], 400 [s], and 600 [s]).

according to the rules. For example, in a head-on situation, the two ships approach each other from bow to bow, and the ship domain of bow is larger than that of stern, while the ship domain of port and starboard is smaller than that of bow and stern. Turning to the starboard side to avoid collision is in line with the rules, so the ship domain on the starboard side is larger than that on the port side. The R-TCR integrates the rule awareness, which is closer to the OOW's cognition and navigation practice.

4. Case study

4.1. Background of the case

To further demonstrate the proposed method, we introduce a case study of a collision accident between the Oil tanker SANCHI and the bulk carrier CF CRYSTAL in the East China Sea on 6th Jan 2018.

At about 1950LT (1150 UTC), Panama registered oil tanker CF CRYSTAL collided with the Hong Kong (China) registered bulk carrier CF CRYSTAL at approximate position 30°51′.1 N / 124°57′.6E. This position is in the open sea, and ample sea room is available. SANCHI, loaded with a cargo of condensate oil, was on her voyage from Assaluyeh, Iran to Daesan, Republic of Korea (ROK). CF CRYSTAL was loaded with sorghum in bulk, bounding from Kalama, the USA to Dongguan, China. The collision breached the cargo tanks of SANCHI, resulting in the leakage of condensate oil, consequent fire and explosions, and eventual sinking of the vessel. At the time of the accident, the weather was cloudy with good visibility, the northeast wind Beaufort force was 4 to 5, and the sea state was slight. As a result, three crew of SANCHI died, and 29 were missing, and pollution occurred. CF CRYSTAL sustained extensive structural damage to her bow and burn damage to other areas.

Table 5 contains the basic information about the two ships. Under the fully loaded condition, the SANCHI's advance is about 0.47 NM at a speed of 10.8 knots and hard starboard. CF CRYSTAL's advance is about 0.375 NM at a speed of 10.06 knots and hard starboard (See appendix for details). Fig. 9 shows the trajectory of the two ships with the AIS data. The starting time of data is about 40 min before a collision occurs; the end time of the data is the time when the collision occurs.

The two ships are in a crossing situation. Ship SANCHI is the give-way ship, and ship CF CRYSTAL is the stand-on ship. According to the trajectory analysis, neither of the ships took evasive actions from the beginning to the end. According to the accident investigation, the main causal factors of the accident are as follows: (1) Both ships failed to keep a proper lookout as required by Rule 5 of the COLREG 1972; (2) Both ships failed to determine if the risk of collision existed as required by Rule 7 of the COLREG 1972.

4.2. Results

Fig. 10 shows the R-TCR of the two ships. In general, the value of R-TCR is small at the beginning. As time goes by, the R-TCR of the ship climbs dramatically. For both SANCHI and CF CRYSTAL, there are oscillations in the rising process of R-TCR value. The R-TCR growth trend of ship SANCHI is even faster than that of ship CF CRYSTAL. R-TCR of SANCHI reaches 1 at 11:42:27, and that of CF CRYSTAL reaches 1 at 11:43:35.

4.3. Discussion of case study

From this case study, we can find some facts:

(1) With the development of the encounter, the R-TCR values of both ships rise, indicating that the maneuvering space to avoid conflict is reducing.
(2) The oscillation of the R-TCR data is related to the quality of ship data extracted from the Voyage Data Recorder.
(3) The R-TCR growth trend of ship SANCHI is faster than that of ship CF CRYSTAL. It implies that the ship maneuverability of CF CRYSTAL is better than that of SANCHI. Furthermore, worse maneuverability results in more difficulty in collision avoidance, which requires an earlier collision warning.
(4) When the R-TCR of SANCHI reaches 1 at 11:42:27, there is no safe rule-compliant conflict solution for ship SANCHI to avoid the collision. However, conflict avoidance can be achieved by ship CF CRYSTAL from 11:42:27 to 11:43:35. When the R-TCR of SANCHI reaches 1 for the first time, the R-TCR of CF CRYSTAL is 0.33, which means that ship CF CRYSTAL still has an opportunity to avoid conflict. In this case, we can consider that when the R-TCR

of the give-way ship reaches 1, it is the time point that the stand-on ship should take actions to avoid the collision [8].

5. Discussions

5.1. Advantages and limitations of the R-TCR

(1) Comparison with traditional collision risk measures

The traditional collision risk method is based on a pair of ships. Thus, the collision risk usually refers to the probability of collision between two ships, ignoring other ships. However, when the ship sails in a dense region, it is difficult to neglect the influence of other ships. Compared with traditional methods, the R-TCR method can estimate the conflict risk in the multiple-ship scenario, see Section 3.2.

Additionally, most traditional methods (such as CRI methods, etc.) rely on the weights given by experts. Since there is no general agreement in determining the weights, the same model might have different outputs with different experts. The construction of R-TCR, however, does not rely on the weights determined by experts, i.e., it is less influenced by the experts' judgments.

(2) Comparison with the original TCR

Compared with TCR, R-TCR is rule-aware, which means that the actions of the OS are determined under the guidance of rules and good seamanship, complying with practice. From Section 3.5, we observe that the R-TCR usually is higher than the TCR, which implies if we ignore the rules and good seamanship (i.e., using TCR), the conflict risk might be underestimated and the alarm might be postponed given the same threshold. Moreover, the ship has fewer rule-compliant solutions using the TCR method than the case using the R-TCR method when the alarm is triggered.

Besides, R-TCR adopts the concept of conflict risk and using the ship domain to construct the dangerous actions instead of the sum of ships' length. In this paper, the violation of ship domain means a conflict between the OS and TSs. This mode of thinking is consistent with the cognition of OOWs. When they determine collision avoidance actions, what they want to do most is to keep a certain distance from the TS, i.e., the TS does not enter the OS's domain. Thus, the conflict risk could be underestimated and even mislead the OOWs if the domain is ignored.

(3) Limitations of R-TCR

The preference of OOWs in collision avoidance is ignored in the proposed R-TCR. In return, the probability of each achievable action chosen by OOWs is assumed to be equal. However, each OOW might have his/her own preference on choosing evasive actions in practice. Thus, to construct a personalized collision alarm system, the preference of the human operators should be studied. In addition, the R-TCR model takes ship maneuverability into account, which requires a precise ship motion model. However, it is still challenging to model the dynamics of the ship precisely. We expect the development of MASS techniques would provide more tools for parameter identification for ships. Besides, the proposed R-TCR is presumed to work in open waters under good visibility. Considering different application scenarios, such as restricted waters and poor visibility, the application range of R-TCR can be further improved. Finally, this model does not consider the motion uncertainty of target ships. To consider the uncertainty of TS's motion, the idea of a probabilistic velocity obstacle algorithm can be incorporated [19].

5.2. Potential of using R-TCR

R-TCR method offers a new perspective to assess conflict risk, which enriches the tools for conflict detection for both manned and unmanned ships. R-TCR method can not only detect the conflict risk but also give a specific risk value. That value indicates the chance for the ship to avoid collisions. The proposed R-TCR has some potential for manned/unmanned ships and traffic management.

For manned ships, R-TCR can provide risk warning to the OOW according to a preset threshold and can remind the OOW to pay more attention, complying with maritime practice and rules from COLREGS. Moreover, by presenting the dangerous actions and achievable actions, R-TCR also supports the OOW to carry out collision avoidance actions.

For maritime autonomous surface ships, the proposed R-TCR offers a tool for the automatic system onboard to assess the collision risk incompliant with the rules and maritime practice. The rule-compliant risk assessment is the foundation of conflict detection and rule-compliant decision making. We expect that the proposed R-TCR incorporating room-for-maneuver, ship domain, and COLREGs can help the MASS detect the approaching dangers as same as which human operators can do and make decisions before too late (i.e., the number of achievable actions equals 0). Additionally, the R-TCR also provides the guideline for taking actions in encounters. Specifically, the MASS needs to take actions before R-TCR reaches 1; when the R-TCR reaches 1, the emergent actions should be considered, e.g., taking initial "rule-violating" actions or cooperating with the target ships. An example of using TCR in collision avoidance system for human-robot cooperation could be found in paper [50].

From the perspective of traffic management, R-TCR can also be used in Vessel Traffic Service (VTS) in open waters, aiming at finding out the TS with the greatest threat to a specific ship. In the development of unmanned ships, there will be a long period of coexistence of unmanned and manned ships, which increases the difficulty of VTS management. To coordinate the marine traffic, a unified standard is needed to evaluate the risk of manned and unmanned ships. The R-TCR integrates the maritime practice and meets the management requirements of VTS in the mixed traffic of manned and unmanned ships. For using the R-TCR in the restricted waters, the construction of the R-TCR should consider the evasive behavior of the ships in the restricted water, which needs further studies.

6. Conclusions

In this paper, we propose a Rule-aware Time-varying Conflict Risk (R-TCR) measure for ship collision avoidance considering the maneuverability of the Own Ship (OS), COLREG rules, and good seamanship. Different from collision risk, the time-varying conflict risk is formulated as the percentage of the achievable actions that lead to violation of the ship domain.

Comparing with traditional CRI methods, the proposed R-TCR measure can be used to evaluate the immediate risk of conflict, judge collision dangers between multiple ships, determine the time to take evasive actions, and recommend collision-free actions (e.g., course). Additionally, the proposed R-TCR may also play a role in Vessel Traffic Service (VTS) in open waters, explicitly identifying the ship with limited room-for-maneuver (or restricted maneuver ship), i.e., the ship with high a R-TCR value. Thus, it also has the potential to be a part of the intelligent maritime system supporting VTS operators in the future. In brief, the proposed R-TCR method offers a new perspective to assess the risk of conflict, enriching the tools for conflict detection for manned ships, unmanned ships, and VTS operators.

Further research directions of the R-TCR are recommended as follows. Firstly, the improvement of the ship maneuvering model is needed since the calculation of the R-TCR is based on the model. Secondly, the human factors should be taken into account, specifically, the preference of the officer-on-watch in finding collision-free solutions. Thirdly, uncertainties should be considered, such as the influence of the environmental disturbances, uncertain actions of TSs, etc. Fourthly, more practical scenarios and evasive actions would be incorporated to construct the R-TCR, such as poor visibility or restricted waters, Traffic Separation Schemes, speed reductions considering different engine types, etc.

Author statement

Mengxia Li: Methodology, Software, Data curation, Writing- Original draft preparation.

Junmin Mou: Data Collection, Reviewing, and Funding.

Linying Chen: Validation, Writing- Reviewing, Editing, and Funding.

Yixiong He: Navigation Experience Supports.

Yamin Huang: Conceptualization, Methodology, Writing- Reviewing, Reviewing, and Funding.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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Appendix A. MMG Models in the Case Study

Figure 11 and 13 show the manoeuvering ability of SANCHI Oil Tanker and CF CRYSTRAL, respectively. Figure 12 and 14 show the simulated turning circles of two ships using MMG models that are used in the construction of R-TCR in the case study. The comparison of manoeuvrability of the two ships is shown in Figure 15.

Appendix B. Infeasible Courses in Scenarios 1 During Collision Avoidance

In the first scenario (Section 3.2), when target ships increase, the available alternations will be reduced. To illustrate the exact courses made impossible by each of the target ships, Fig. 6A is added. In Fig. 6A, the available alternatives (courses) are colored in light green, and the dangerous alternatives (courses) are colored in brown. The first column in the figure shows the encounter at time 200 s, and the rows show that the OS encounters with TS1 along (Row 1), TS1+TS2 (Row 2), and TS1+TS2+TS3 (Row 3).

Fig. 16. B.

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