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Collision risk measure for triggering evasive actions of maritime autonomous surface ships

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ABSTRACT

Collision risk assessment is essential for supporting collision avoidance, which is the core of various collision alert/avoidance systems. One main task of the systems is setting off alarms for taking evasive actions. The alarms need to be triggered before the conflict has no collision-free solution. However, most of existing collision risk measures are independent of conflict resolution. That means the collision alert does not indicate that the collision is avoidable or not. This article proposes an improved time-varying collision risk (TCR) measure, bringing in a new measure. The measurement of TCR reflects not only the dangerous level of the approaching ships but also the difficulty of avoiding collisions. By comparing with traditional measures, e.g., Collision Risk Index (CRI), we found that (1) the TCR can distinguish changes of risk that have identical CRI level, (2) the TCR measure offers a reasonable tool to evaluate the collision risk of entire traffic, and (3) it reflects the influence of maneuverability improvement on collision risk. Based on those results, this article reaches two conclusions: the collision risk is monotonically increasing when introducing more ships, and ignorance of ship maneuverability results in an underestimation of collision risk.

1. Introduction

Ship collision is a major type of accidents at sea that usually results in significant financial loss, fatalities, and environmental pollution. Thus, relevant collision risk mitigations have been the main research focuses in decades. One traditional mitigation is developing various navigational assistant systems that remind the officer on watch (OOW) to take actions in time. These systems are the so-called collision alert systems. Although such systems have been developed for decades, human error is still the main causations, specifically “response too late” and “omission” (Graziano et al., 2016). To reduce/eliminate human errors on-board, some researchers turn to develop a ship which can operate independently of human interaction called Maritime Autonomous Surface Ship (MASS), and has attracts numerous attention recently. The MASS includes a system that can avoid collisions automatically, which is called collision avoidance system.

Neither in manned ships or unmanned ships, one essential module of the various alarm/avoidance systems is called conflict detection that assesses the collision risk and triggers subsequent events, e.g., setting off alarm, taking evasive actions, etc. Specifically, conflict detection is employed to answer the following three sub-questions (SQs):

SQ1: who (or which ship) will strike the own-ship (OS)? (collision candidates)
SQ2: when the OS needs to pay attention to the dangers? (collision alert)
SQ3: when the OS needs to (has to) take evasive actions? (time for evasive actions)

Many measures have been developed to assess the risk for solving these SQs. A remarkable method is using the concept of Closest Point of Approach (CPA), which is popular in both maritime and aviation studies Radanovic et al. (2018). Two widely accepted indicators related to CPA are Distance to CPA (DCPA) that shows the minimal distance between two ships, and Time to CPA (TCPA) that shows the time left for the ship reaching CPA. For instance, Chin and Debnath (2009) constructed a Collision Risk Index (CRI) via combining DCPA and TCPA linearly; Goerlandt et al. (2015) introduced many indicators including DCPA and TCPA to construct their CRIs. Those methods showed a good performance in identifying collision candidates (i.e., SQ1) and making a relevant precaution (i.e., SQ2). However, few of them can handle the SQ3 for following two main limitations.

(1) Being independent of the conflict resolution.

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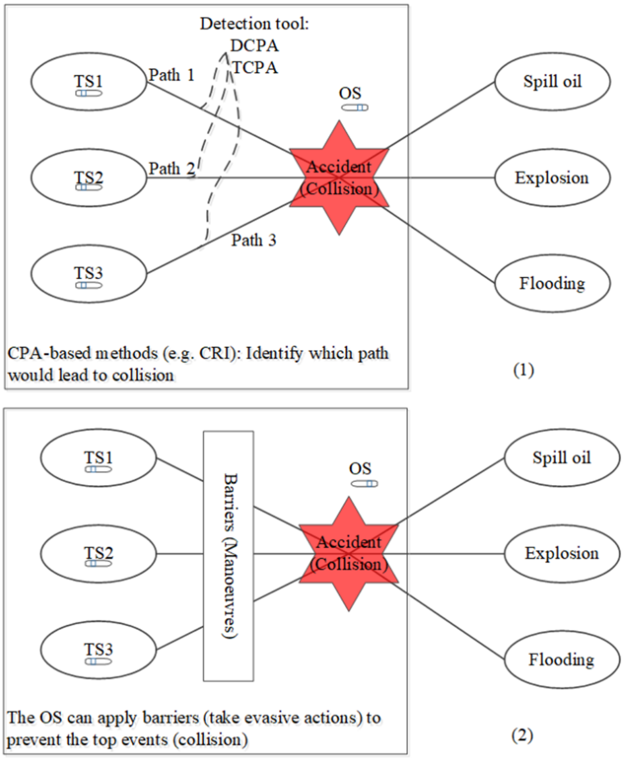

Fig. 1. Illustration of Bow-Tie model of collision event (1) without & (2) with barriers.

SQ3 requires that the risk measure is formulated in such a way that it allows for sufficient time to trigger evasive actions before the conflict becomes unavoidable. Thus, the formulation of risk needs to associate with conflict resolutions.

However, most existing risk measures are independent of conflict resolutions. Thus, the high risk does not indicate the collision is unavoidable or not. In returns, these methods might result in one type of failure, i.e., no alarm is triggered until the collision is unavoidable (Goerlandt et al., 2015). Additionally, few risk measures can reflect the impacts of ship maneuverability on collision risk. Although researchers believed that good maneuverability contributes to safety (Li et al., 2005), which motivates the studies on improving the maneuverability of ships, little research addresses the problem how does the risk change due to the improvement of maneuverability.

Furthermore, by using "Bow-Tie" theory in collision analysis, we believe that incorporating conflict resolution is necessary for measuring collision risk for SQ3. In the "Bow-Tie" of collision process (see Fig. 1), the "threats" are the target-ships (TSs), "top event" is a collision accident, the "consequence" refers to damages, and the "barrier" is maneuvers from the OS, i.e., the conflict resolution. The traditional measures only appraisal the possibility of the "threat" reaches the "top-event" and ignores the function of "barrier", see Fig. 1(1). However, the OS enables to prevent the accident by using "barriers", i.e., maneuvers or conflict resolutions, see Fig. 1(2). Thus, the assessment of the probability of "top event" needs to be associated with "barrier", i.e., conflict resolutions.

(2)
Depending on pairwise encounters

Most existing risk measures focus on pairwise encounters, i.e., the encounter involving a pair of ships. Those measures usually assess the risk of pairwise ships separately and ignore the impacts of other ships. Thus, the changes in risk when the OS encounters with multiple ships cannot be reflected. In other words, these measures cannot tell the users about the entire risk of collision when the ship encounters with more than one ship.

Furthermore, when decoupling the traffic into several pairs of ships, we lose some information and introduce some biases in risk measures. The biases of risk are caused by two aspects: (1) the risk caused by a non-conflicting TS is ignored. Although a non-conflicting TS does not directly have a conflict with the OS at present, it might block some operations of the OS, which can indirectly result in an inevitable collision between the OS and another TS; (2) the risk caused by traffic characteristics is ignored. For example, in some case, well-organized traffic seems to be safer than the traffic in chaos.

This paper improves the measure of Time-Varying Collision Risk (TCR) proposed in (Huang and van Gelder, 2020). The TCR measures the collision risk as the percentage of the achievable maneuvers leading to collisions. Specifically, the following improvements have been made: (1) Generalized Velocity Obstacle (GVO) algorithm incorporating ship dynamics is introduced to identify dangerous maneuvers and reachable maneuvers; (2) kinematic constraints and dynamic constraints are considered in the construction of reachable sets.

Based on the improved TCR measure, the following findings are concluded:

(1) Traditional CPA methods and some CRI methods may lead to failure (i.e., alarm too late) under some circumstances;
(2) By introducing one more TS, the collision risk from the perspective of the OS would not be reduced;
(3) Collision risk is underestimated when the maneuverability is ignored.

The structure of this article is organized as follows: the background of collision risk measure is addressed in Section 1, followed by a review on existing collision-risk measures in Section 2. The fundamental idea of TCR measure and relevant improvements have been presented in Section 3. In Section 4, comparisons of traditional measures and the TCR measure in various scenarios are presented. Discussion and conclusion are addressed in Section 5 and Section 6, respectively.

2. Literature review

Many accidents are caused by late response or no response (Graziano et al., 2016; Sandhåland et al., 2015). Even for MASS, researchers consider the "responding too late" would be one main type of errors of human operators in the off-shore center (Abilio Ramos et al., 2019). These concerns are all related with SQ3 addressed in Section 1. Therefore, in this section, we overview the existing risk measures, especially their capability of handling the SQs.

2.1. Overview of existing risk measures

In (Huang et al., 2020), two main groups with 6 types of risk measures are identified. They are expert-based methods and model-based methods. The expert-based methods usually reply on experts' judgment, and the risk value reflects the belief of experts about the collision event. The model-based methods usually simplify scenarios, and the risk indicates the probability of collision in the simplified scenario. Table 1 provides an overview of these two groups. The details of studies using these methods in conflict detection have been shown in

Table 1
Overview of existing risk measures.

Group	Types	Explanations	Reference
Expert-based method	CRI	Collision Risk Index (**CRI**) uses an index to describe the risk, which combines various indicators. (read more in Table A1 in Appendix A)	Chin and Debnath (2009), Lopez-Santander and Lawry (2016)
	WR-SD	Warning Ring based on Ship domain (**WR-SD**) sets off an alarm when another ship violates or will violate the ship domain around the ship. (read more in Table A2 in Appendix A)	Tam and Bucknall (2010), Wang (2012), Zhang and Meng (2019).
Model-based method	CPA	sets off an alarm when key indicators (DCPA and TCPA) meet the threshold;	Hilgert and Baldauf (1997)
	Pcoll	Probability methods (**Pcoll**) calculate the probability of collision based on known and limited uncertainties.	Park and Kim (2016), Shah et al. (2015)
	DR	Dangerous Region (**DR**) presents the dangerous area to user and sets off an alarm when the state (e.g. velocity) of the ship falling inside the dangerous region.	Su et al. (2012), Szlapczynski and Szlapczynska (2015)
	ActLines	Action Lines (**ActLines**) plot virtual curves around the OS to remind the ship to take pre-set actions.	(Michael Baldauf, Mehdi, Fischer, & Gluch, 2017; Szlapczynski, Krata, & Szlapczynska, 2018).

Limitations of the existing measures for conflict detection have been shown in Table A3.

Traditionally, CPA has been seen as the solutions to all these SQs, and it had been integrated into radar on board for supporting collision avoidance. The logic of using CPA methods in conflict detection is addressed as follows:

A1: the TS whose DCPA is smaller than safety distance is the ship will stride the OS;
A2: as long as the TS will collide with the OS, the collision alert is triggered;
A3: when the alert is triggered, the OS needs to take evasive actions.

However, this logic might lead to frequent alerts in dense waters. Thus, the OOWs usually turn off the alert systems (Fukuto and Imazu, 2013; Motz et al., 2009). In dense regions, a ship could easily have a conflict with the OS, but not all the conflicts require the OOW to pay special attention or take evasive actions immediately. Many factors need to be considered, e.g., time to collision, the obligations of the regulation (COLREGs), the OS's maneuverability, etc.

To reduce the frequent false alarms when using the CPA method, expert-based methods are introduced, which mainly focus on solving SQ2 and triggering collision alert according to experts' expectations. One representative method is CRI that combines DCPA, TCPA, and other indicators to adjust the frequency of false alarms. DCPA and TCPA are still two core indicators in various CRI methods (Ozturk and Cicek, 2019). The selection of other indicators and the construction of these indicators highly rely on the experts' knowledge. Later on, the development of "ship domain" inspired another group of researchers to present the collision risk as warning ring instead of a numerical index, which is intuitive for the users. These methods are named as WR-SD methods. The expert-based methods are capable of handling SQ2, while they might not suitable for SQ3. The ignorance of conflict resolution and ship maneuverability are the main limitations. Hence, the violation of the thresholds of CRI methods or WR-SD methods does not indicate the collision is avoidable or unavoidable.

Some model-based methods in Table 1 that consider conflict resolution could fill this problem, e.g., DR methods and ActLine methods, but they also suffer from some limitations. DR methods support the users to identify the collision candidates (SQ1) easily, while ship maneuverability is usually ignored; ActLine methods consider the ship maneuverability and identify the last moment in time to take actions, while they are not suitable for multiple-encounter scenario.

Not only DR methods and ActLine methods, many risk measures evaluate the collision risk in a pairwise encounter and treat multiple encounters as multiple pair-wise encounters (Goerlandt et al., 2015) (see Table 2). The pairwise measures show the threats from each TS to the OS separately, and these measures temporarily ignore the influence of other ships. In this way, the collision risk in each pairwise is clear, but the entire collision risk level from the OS perspective is unclear. However, the entire risk level is crucial for solving SQ3. For instance, in multiple-encounter scenario, the risk level in each encounter is low, which implies the OS has collision-free solutions with each TS. However, when the OS encounters with all the TS together, the OS might not find any collision-free solution. Thus, there is a need to assess the entire collision risk for handling SQ3.

2.2. Summary of conflict detection techniques

In brief, collision risk measure plays an important role in triggering evasive actions in collision avoidance, which determines the (last) timing for the ship to take actions. However, few of the existing measures are capable of handling all the SQs, especially SQ3.

Firstly, existing methods are not applicable to the multiple-encounter scenarios that frequently occur in dense waters. The assessed risk only reflects the danger level of each approaching ship rather than the danger/safety level of the OS facing all the apporaching ships together. Thus, in the multiple-encounter scenarios, the existing methods cannot address the risk of collision and the changes on risk when the number of TSs is changed. Secondly, the existing measures neglect the ability of the OS to avoid collisions, and the risk level is relatively independent of the collision prevention events. That means the violation of the risk threshold does not indicate that the collision is avoidable or not.

From many investigation reports, "action too late" is the major causation of collisions and a late action often attribute to a late detection (Graziano et al., 2016). Thus, a proper risk measure is needed, which can not only identify the potential dangers but also trigger an alarm before the ship cannot solve the conflict. Thus, there is a need for incorporating conflict resolutions in risk measures that also handle multiple-encounter cases.

3. Time-varying collision risk for collision avoidance

In this manuscript, the risk is defined as the probability of an unwanted event. Thus, the collision risk is the probability of the collision event.

3.1. Fundamental time-varying collision risk

Time-varying Collision Risk measure proposed in Huang and van

Table 2
Overview of collision risk measures in existing studies.

Name	Form & Range	Method	Meaning of Violations	Main Purpose			Multi-encounter
				SQ 1	SQ 2	SQ 3	
CRI	numericalR^+	Synthetic indicators	Experts believe this TS is dangerous for the OS and needs special attention.	√	√	–	P
WR-SD	graphical[R^+]	Expanding of ship domain	**FSD:** experts believe this TS will get too close to the OS. Thus, this TS is dangerous for the OS.	√	√	–	P
			SDR/Arena: experts believe this TS is too close to the OS and needs special attention.	√	√	–	P
CPA	numerical [0/1]	Closest position given scenario	This TS will strike the OS if two ships keep their velocity.	√	–	–	P
P_{coll}	numerical [0–1]	Probability of overlapping with known distribution	This TS probably will strike the OS given measured uncertainties.	√	–	–	P
DR	graphical[0/1]	present a risk map in terms of velocity. (equivalent to DCPA)	The OS will strike with one of TSs if the OS keeps its velocity and all the TSs keep their velocity.	√	–	–	M
ActLine	graphical[0/1]	Simulation of encounter with pre-set actions of the OS	This TS will strike the OS if the OS takes a certain action or the OS cannot avoid collision with this TS by the certain action.	–	–	√	P

Notes CRI: Collision Risk Index; DR: Dangerous Region; P_{coll}: Collision Probability. R^+: positive real number; [R^+]: positive real number in a range, i.e., 0–1; "0/1": 0 or 1; "0–1": 0 to 1. FSD: Fuzzy Ship Domain; SDR: Spatial Danger Region. "√" means the method is suitable for solving the sub-question; "-" means the method is not suitable for the sub-question. P: Pairwise-based method; M: Multiple-based method.

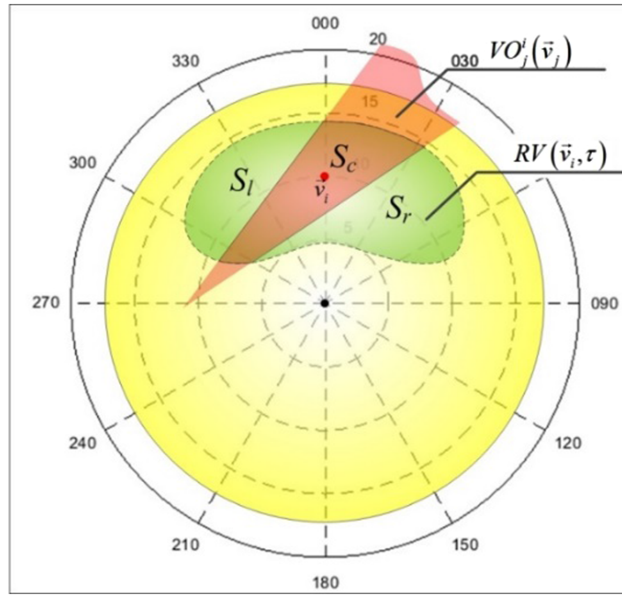

Fig. 2. Illustration of the dangerous set and the reachable set in the velocity space of the OS. (note: a point in this space represents a velocity of the OS: the axes indicate the course; the distance from the pole represents the speed).

Gelder (2020) is developed to incorporate conflict resolution in collision risk measure. The risk is defined as the time-dependent probability of the event that OS cannot avoid a collision with TSs. Specifically, the risk is measured as the percentage of maneuvers leading to collisions to its all feasible maneuvers before a collision:

$$\mathrm{TCR}(t) = \sum_{i=1}^{n} P(collision|\vec{v_i}, x(t))\cdot P(\vec{v_i}, x(t)) = \frac{n_{\mathrm{collision}}(t)}{n(t)} \tag{1}$$

where $n_{\mathrm{collision}}(t)$ is the number of maneuvers leading to collisions at time t; $n(t)$ is the number of reachable maneuvers before collisions at time t.

The keys of Eq. (1) are identifying two sets. One set collects the maneuver leading to collisions, say dangerous set, and the other one collects the reachable maneuver, say reachable set. An illustration is shown in Fig. 2. The dangerous set is colored in red, and the reachable set is in green.

Let denote S_c as the intersection of the reachable set and the dangerous set, and $\bar{S}_c(t)$ as the complement of S_c in the reachable set. Thus, TCR for the OS can be interpreted as the proportion of S_c to the reachable set ($S_c + \bar{S}_c$):

$$\mathrm{TCR}(t) = \frac{\mathcal{N}(S_c(t))}{\mathcal{N}(S_c(t) + \bar{S}_c(t))}, \tag{2}$$

where $\mathcal{N}(\cdot)$means the size of a set.

3.2. Improved TCR measure

In the original article, constructions of the dangerous set and the reachable set are independent. The dangerous set is identified by Velocity Obstacle (VO) algorithm that ignores the OS's maneuverability, and the construction of the reachable set incorporates the maneuverability. This method basically presumed the dangerous maneuver set is invariant when the ship steers from the initial velocity to any reachable velocity. However, when the OS steers from the initial velocity to another velocity, the encounter situation between the OS with the TS is not invariant. The encounter situation is changing, and

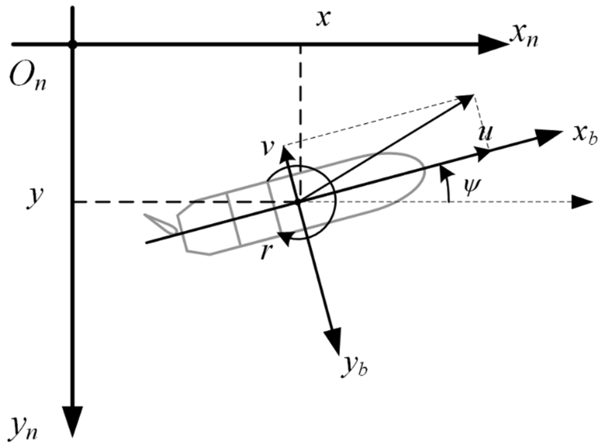

Fig. 3. Illustration of the inertial frame {n} and the body frame {b} for a ship.

the dangerous set is changing, as well. When the distance between the two ships is large enough, these changes can be ignored. However, this case might not apply in a close-range encounter.

To handle this problem, we use the generalized velocity obstacle (GVO) algorithm to construct the dangerous set and the reachable set together. The GVO algorithm was proposed in Bareiss and van den Berg (2015), which incorporated the dynamics of vehicles. An application of using GVO in the maritime domain is demonstrated in Huang et al. (2019).

Similar to the VO algorithm, the GVO algorithm also identifies the maneuver leading to a collision, while the maneuver refers to the change of velocity, i.e. Δu. The reachable set then refers to the maximal changes of velocity regarding various constraints, e.g., maximal power of the ship in different directions, etc.

3.2.1. Ship dynamics model

The vectorial representation of ship dynamics introduced by Fossen (2002) is used, i.e.,

$$\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} \dot{\mathbf{x}} = \begin{bmatrix} \mathbf{R}(\psi)\mathbf{v} \\ -\mathbf{C}(\mathbf{v})\mathbf{v} - \mathbf{D}(\mathbf{v})\mathbf{v} \end{bmatrix} + \mathrm{B}\tau, \tag{3}$$

where $\mathbf{x} = [\eta^{\mathrm{T}} \quad \mathbf{v}^{\mathrm{T}}]^{\mathrm{T}}$ and τ is the input force vector. η contains coordinates (x, y) and heading (ψ) in the inertial frame. $\mathbf{v}$ consists of the linear velocities (u, v) and angular velocity (r) in the body frame. An illustration is presented in Fig. 3. Input $\tau$is composed of surge force, sway force and torque (i.e., $[\tau_u, \tau_v, \tau_r]^{\mathrm{T}}$). $\mathbf{M}$, $\mathbf{C}(\mathbf{v})$, $\mathbf{D}(\mathbf{v})$, and $\mathbf{R}(\psi)$ are inertia matrix, Coriolis–centripetal matrix, damping matrix, and rotation matrix, respectively.

Moreover, we add a PD controller as a high-level controller and switch the control input from the force τ to the desired velocity $\mathbf{u}$. The PD controller is formulated as:

$$\tau = \mathrm{K_p}(\mathbf{u} - \mathrm{V}\mathbf{x}) - \mathrm{K_d}\mathrm{V}\dot{\mathbf{x}}. \tag{4}$$

The new system with the PD controller uses the desired velocity as inputs (i.e., $\mathbf{u}$):

$$\begin{aligned} \dot{\mathbf{x}} &= \left(\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} + \mathrm{BK_d V} \right)^{-1} \\ &\quad \begin{bmatrix} \mathbf{R}(\psi)\mathbf{v} \\ -\mathbf{C}(\mathbf{v})\mathbf{v} - \mathbf{D}(\mathbf{v})\mathbf{v} - \mathrm{K_p V}\mathbf{x} \end{bmatrix} + \left(\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} + \mathrm{BK_d V} \right)^{-1} \mathrm{BK_p}\mathbf{u} \\ &= \mathbf{f}(\mathbf{x}, \mathbf{u}). \end{aligned} \tag{5}$$

Since Eq. (5) is non-linear, we can approximate the state of the ship with the help of Runge-Kutta (RK) Integration and Taylor expansion law. Specifically, we can formulate the position of the ship at time t via the changes of the desired velocity, $\Delta\mathbf{u} = \mathbf{u} - \mathbf{u}(0)$.

$$\mathbf{x}(t) \approx \int_0^t \mathbf{f}(\mathbf{x}^0, \mathbf{u}^0)d\tau + \int_0^t \Delta\dot{\mathbf{x}}(\tau)d\tau = \tilde{\mathbf{x}}(t) + G(t)\Delta\mathbf{u}, \tag{6}$$

where $G(t) = \int_0^t e^{A(t-\tau)}Bd\tau$(with $A = \mathbf{f_x}$and$B = \mathbf{f_u}$) and $\tilde{\mathbf{x}}$ is the estimated state of the ship calculated via RK method with a known initial state $\mathbf{x}^0$ and a known initial input $\mathbf{u}^0$.

3.2.2. Using GVO to identify dangerous maneuvers

Given Eq. (6), the position of the ship at time t is formulated as:

$$\mathbf{P}_i(t) = C\tilde{\mathbf{x}}_i(t) + CG(t)\Delta\mathbf{u}_i, \tag{7}$$

where $C = [\mathbf{I}^{2\times2}, \mathbf{0}^{2\times4}]$ contains a 2-by-2 identical matrix and a 2-by-4 zero matrix. Thus, the necessary condition of collision at time t is presented as:

$$\mathbf{P}_i(t) \in \mathbf{P}_j(t) \oplus ConfP, \tag{8}$$

ConfP is the adjacent safety region surrounding the target ship. Thus, Eq. (8) means the OS violates the safety region of the TS. By solving Eq. (8), a sub-set of changes of the desired velocity leading to collision at time t is collected, i.e.,

$$\Delta\mathbf{u}_i \in (CG(t))^{-1}\cdot[-(\tilde{\mathbf{P}}_i(t) - \mathbf{P}_j(t)) \oplus ConfP] = \mathrm{sUO}(t), \tag{9}$$

Then, the changes in the desired velocity leading to collision at any time are the union of subsets, i.e.,

$$\mathrm{UO} = \bigcup_t^{\infty} \mathrm{sUO}(t). \tag{10}$$

3.2.3. Using GVO to formulate the reachable maneuvers

So far, the maneuvers leading to collision is formulated (in Eq. (10)), and the construction of the reachable set is equivalent to the problem that finds the boundaries of the desired velocity $\mathbf{u}^*$ given constraints on maximal input forces. Let say, the force in each direction is satisfying constraints:

$$\tau_{\mathbf{lb}} \leqslant \tau \leqslant \tau_{\mathbf{ub}}. \tag{11}$$

Then, we substitute Eq. (6) into Eq. (4) to have an expression of forces with respect to the desired velocity $\mathbf{u}^*$, i.e.,

$$\tau = (K_p - K_d V f_2)\mathbf{u}^* - (K_p V\mathbf{x} - K_d V f_1), \tag{12}$$

where $f_1 = \left(\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} + \mathrm{BK_d V} \right)^{-1} \begin{bmatrix} \mathbf{R}(\psi)\mathbf{v} \\ -\mathbf{C}(\mathbf{v})\mathbf{v} - \mathbf{D}(\mathbf{v})\mathbf{v} - \mathrm{K_p V}\mathbf{x} \end{bmatrix}$ and $f_2 = \left(\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} + \mathrm{BK_d V} \right)^{-1} \mathrm{BK_p}$.

Combining Eqs. (12) and (11), we derive the constraints on the desired velocity $\mathbf{u}^*$:

$$\begin{aligned} &\mathbf{u}^* \in \mathbf{U}^1 \\ &= (K_p - K_d V f_2)^{-1}[(\tau_{\mathbf{lb}} + K_p V\mathbf{x} - K_d V f_1), (\tau_{\mathbf{ub}} + K_p V\mathbf{x} - K_d V f_1)]. \end{aligned} \tag{13}$$

Eq. (10) is the reachable velocity set with respect to constraints on forces and the designed PD controller.

Besides, the ship also needs to meet some kinematic constraints. For instance, the maximal desired course might not exceed 180 degrees in the port side and the starboard side; the maximal speed might not

Table 3
Parameters of the setup of the OS (using Froude scaling factors).

	Scaled model	Full scale (1:70)
B	0.290 [m]	20.30 [m]
L	1.255 [m]	87.85 [m]
d_{CPA} (4.25*L)	5.334 [m]	0.2 [NM]
$\tau_{\mathbf{ub}}$; $(-\tau_{\mathbf{lb}})$	$[10,10,10]^T$	$[3430000, 3430000, 240100000]^T$
Speed u_0	0.615 [m/s]	10 [knots]
K_p	[200, 200, 10]	–
K_d	[5, 5, 5]	–

exceed the constraint. In brief, these constraints are formulated as:

$$\mathbf{u}^* \in \mathbf{U}^2 = \begin{bmatrix} u_{\min}, u_{\max} \\ \psi_{\min}, \psi_{\max} \end{bmatrix}. \quad (14)$$

The final reachable set is the intersection of Eqs. (13) and (14), i.e.,

$$\mathbf{u}^* \in \bigcap_{i}^{2} \mathbf{U}^i. \quad (15)$$

4. Comparison with traditional risk measures

In this section, some simulations are presented to show the characteristics of the improved TCR measure in various encounter scenarios and to compare with some popular risk measures in the literature, e.g., CRI_1, CRI_3 in Table A.1.

4.1. Setups of the OS

In these simulations, the model ship "CyberShip II" has been employed as the OS. TSs are identical to the OS, while they are presumed to keep their speed and course. The details of the "CyberShip II" is

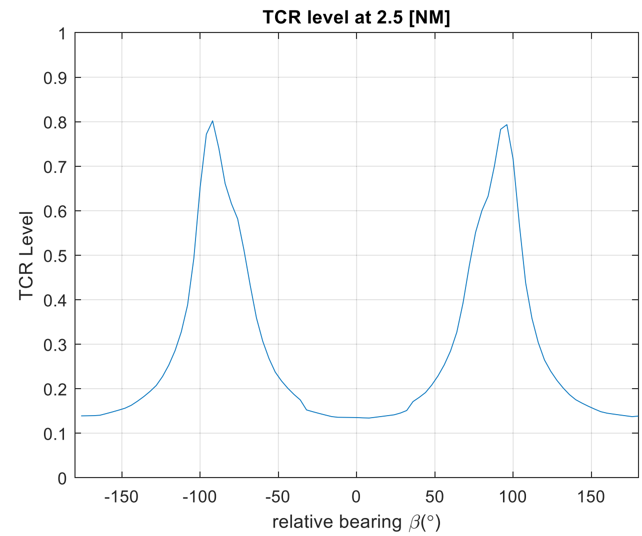

Fig. 5. TCR level at different relative bearing when DCPA, TCPA, and d_{ij} are the same.

Table 4
Setting of TSs encounter scenarios.

	TS1	TS2	TS3
Position [NM]	(0.2280,0.2432)	(0.6647,-0.0514)	(-0.1347,0.9909)
Speed [knot]	8.51	11.25	3.51
Course [deg]	349.7	336.8	075.2
DCPA [NM]	0	0	0
TCPA [h]	0.15	0.15	0.15

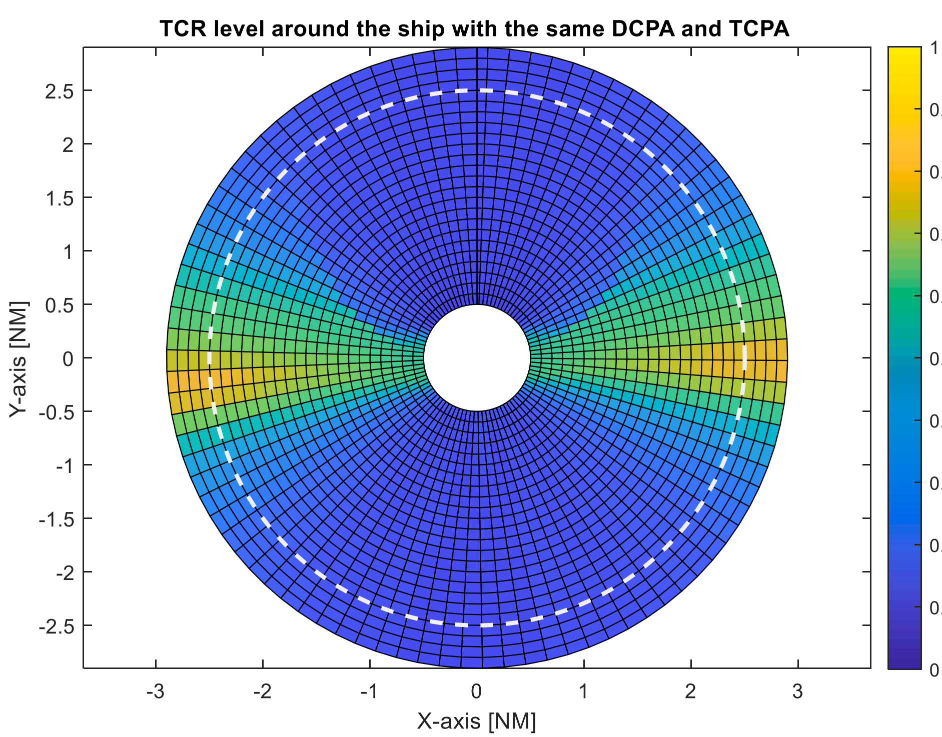

Fig. 4. Distribution of TCR when DCPA and TCPA remain the same.

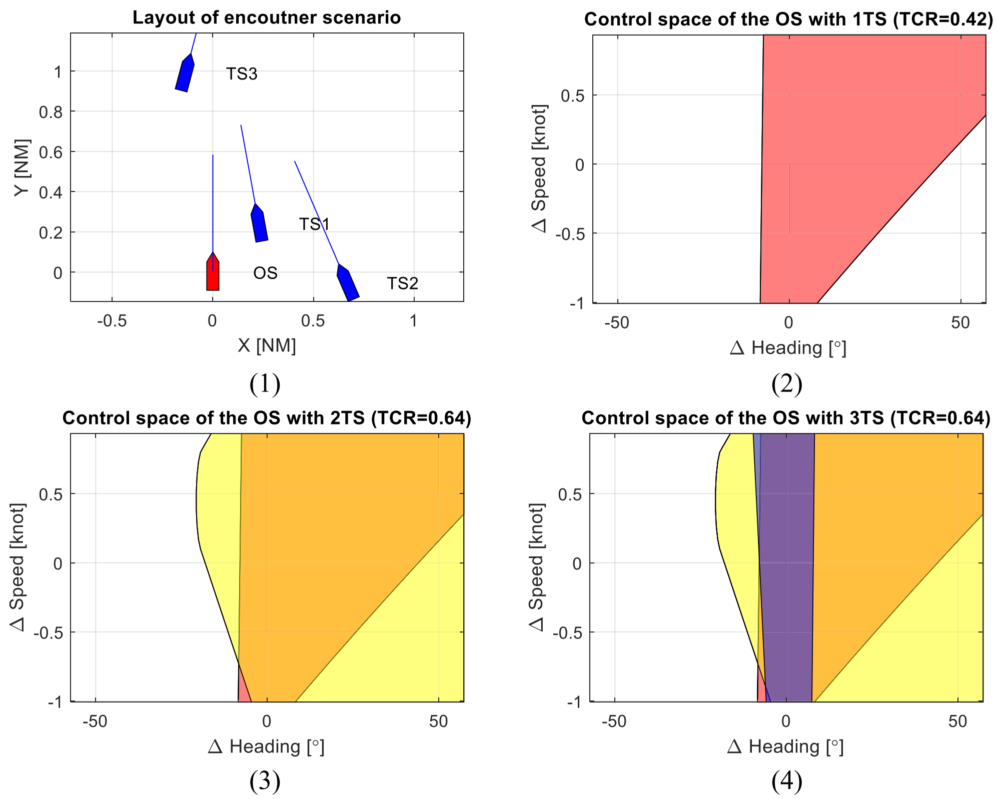

Fig. 6. Scenarios with one TS, two TSs, and three TSs and the relevant control spaces.

Table 5
Settings of ships in standard group and control groups.

	Force Boundary	Setting of TS				
	($\tau_{ub} = -\tau_{lb}$)	Position [NM]	Speed [knot]	Course [deg]	DCPA [NM]	TCPA [h]
Standard group	$\tau^0_{ub} = \begin{bmatrix} 3430000 \\ 3430000 \\ 240100000 \end{bmatrix}$	(1.5, 0.5)	12.02	303.7	0	0.15
Control group 1(+30%)	$\tau^1_{ub} = \tau^0_{ub} \times 1.3$					
Control group 2(-30%)	$\tau^1_{ub} = \tau^0_{ub} \times 0.7$					

presented in (Skjetne et al., 2004). The scale factor of this model ship is 1/70. Thus, some key parameters are shown here, which are re-scaled to the physical world (see Table 3).

In the following simulators, the OS is placed at the origin heading to the North with speed 10 [knots]. The safety region *ConfP* is shaped like a circle of which the radius is 4.25 times of ship lengths, which is slightly larger than the long axis of the Fujii's ship domain. d_{CPA} is set as the same as the radius of ConfP. Moreover, the violation of the safety region is unacceptable, which could be seen as an unwanted event.

4.2. Distribution of risk when DCPA and TCPA are invariant

Many risk measures are only relying on two indicators called DCPA and TCPA. The DCPA shows how close the approaching TS would be, and the TCPA shows the time left for this TS reaches the CPA. Hence, some methods design criteria using DCPA and TCPA to trigger alarms for precautions, triggering evasive actions, and choosing collision-free actions.

One representative group of methods sums the value of DCPA and TCPA with assigned coefficients as one value called CRI. This group is noted as CRI_1 in this article. Moreover, another group of methods, using DCPA, TCPA, and relative distance (d_{ij}) as inputs and calculate the CRI by using the Euclidean norm, which is denoted as CRI_3. These methods basically announce that if the DCPA, TCPA, and d_{ij} of two TSs are the same, the collision risk of these TSs is identical for the OS.

Argument 1: When the OS encounters with the TSs whose DCPA, TCPA, and d_{ij} are the same, the collision risk of these TSs are also identical.

To test this argument, we simulate a number of two-ship encounter scenarios and maintain the value of DCPA and TCPA in each scenario. The DCPA and TCPA are set as 0.15 [NM] and 0.15 [h], respectively. Then, we calculate the chance of the OS successfully avoid the collision in each scenario via TCR measure. In each scenario, the TS is placed around the OS, and its velocity is adjusted to maintain the pre-determined DCPA and TCPA. The simulation is repeated until all the positions surrounding the OS have been traversed.

The simulation results have been presented in Fig. 4 as a disc. The TS was placed at each grid ranged from 0.5 to 2.9 [NM]. The color in the grid shows the value of TCR that reflects the chance of avoiding collision by pre-set Cybership II and its PD controller. The color in blue shows that the OS has a high percentage of control inputs can successfully avoid the collision, i.e., keep its safety region clear. The color in yellow shows that most control inputs of the OS would lead to violation of the safety region, i.e. collision.

In this disc, the TS at each position has the same DCPA and TCPA. Thus, using CRI_1 methods, the collision risk level would be the same at each position. However, as we presented in Fig. 4, the TCR levels at each position are different. A higher TCR implies the OS has fewer

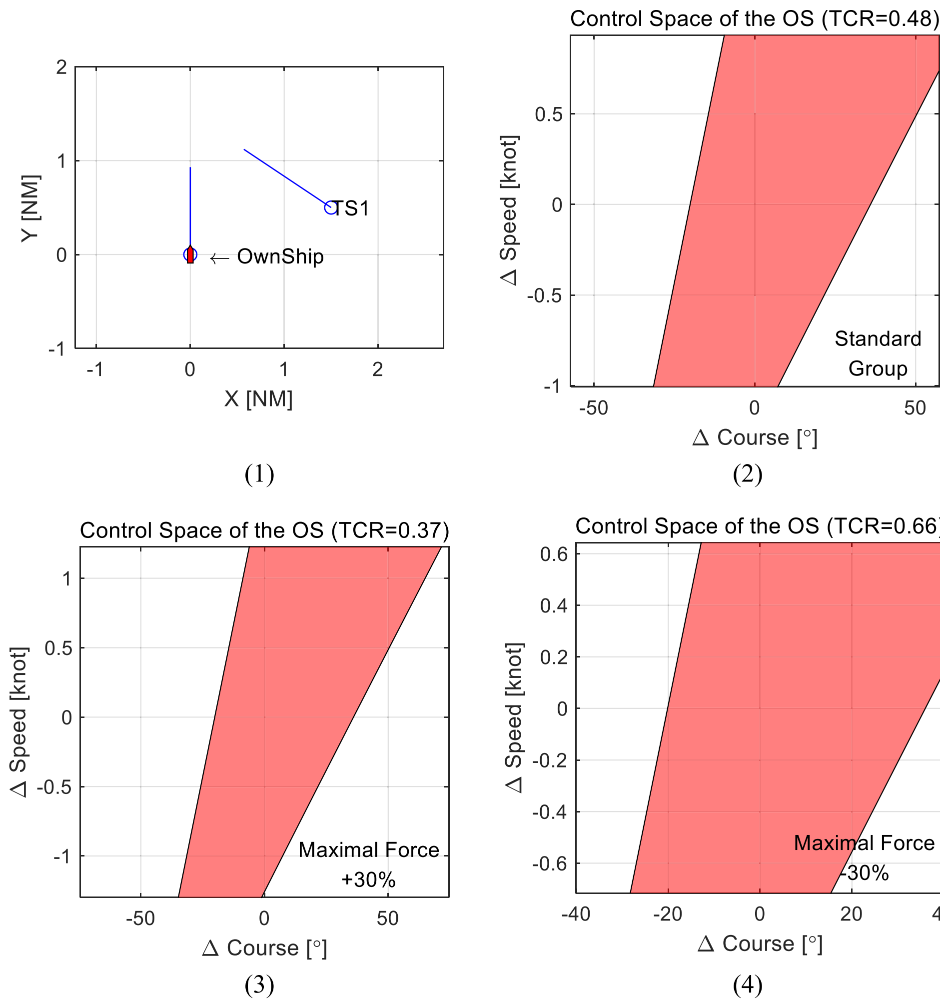

Fig. 7. Encounter scenario in Standard Group and Control Groups with presentations of control space.

collision-free solutions, i.e., fewer chances to be safe. When the TCR reaches 1, the collision is inevitable with the given settings. Specifically, when the TS appeared at the port beam or the starboard beam, the TCR is high, which indicates the OS has limited solutions to avoid the collision.

Additionally, by cutting the ring in Fig. 4, we get the changes of TCR level when the distance between the TS and OS is 2.5 [NM] in Fig. 5. The TS is placed at different positions around the OS while the indicators, DCPA, TCPA, and d_{ij}, are the same. According to CRI_3, when the values of these indicators are the same, the collision risk would be the same. However, from the perspective of conflict resolution, the risk would be different. Two pinks appear at the relative bearing ± 90°. The results imply the heading scenarios and overtaking scenarios are relatively easier for the OS to avoid the collision. Moreover, based on the finding in this section, we conclude Remark 1.

Remark 1: Even the OS encounters with one ship whose DCPA, TCPA, and relative distance are all identical to another ship in another encounter, the collision risk of these two cases are different.

4.3. Changes of risk when the ship encounters with one more ship

Traditional methods, such as CRI methods, WR-SD methods, Pcoll methods, CPA methods, and Action lines, are usually based on two-ship encounter scenarios. In return, these methods might not point out the change of collision risk when the ship encounters one more TS. TCR measure can handle this issue.

By introducing one more ship, the number of collision-free solutions would be reduced. That means it is difficult for the OS to find a collision-free solution. Then, the collision is likely to happen, and the risk would increase.

To show this feature, we design three scenarios with one TS, two TSs, and three TSs. The DCPA and TCPA of these TSs are identical. Thus, by using CRI_1, the collision risk between the OS and any TS is identical. Settings of encounter scenarios are shown in Table 4. The layout of the encounter scenario is presented in Fig. 6.

In the first scenario, the OS encounters with TS1 only, and the controls leading to collision (i.e., violation of safe region) are presented as a red region in Fig. 6(2). In this figure, the current control is located at the origin, i.e., no changes in existing heading or speed. Since the origin is in a dangerous region, the collision would happen in the future. Moreover, the TCR reaches 0.42 means the chance for the ship to avoid the collision is 0.58.

In the second scenario, the OS encounters TS1 and TS2 together, and the controls leading to collision are colored in red and in yellow, see Fig. 6(3). The yellow region is the adding controls leading to collision with the TS2. Due to the additional target ship, the collision-free space is reduced. That means the room for the OS avoiding collision is reduced. Thus, the collision risk is increasing.

In the third scenario, the OS encounters three TSs together, and the control space of the OS is shown in Fig. 6(4). The control inputs leading to collision with TS3 is colored in purple. Different from the second scenario, the additional ship (TS3) does not increase the TCR level because all the controls leading to collide the TS3 (the purple region) have been collected in the dangerous set that leads to collide TS2 or TS1

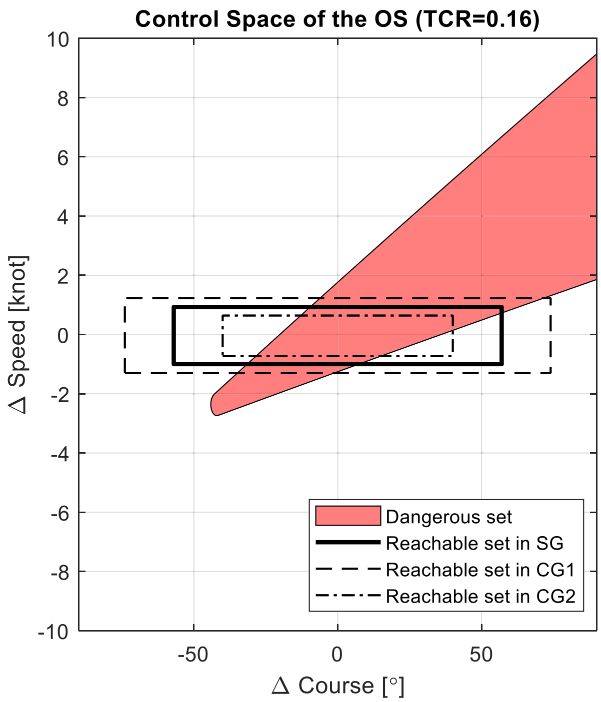

Fig. 8. The control space of the OS if the maneuverability constraints are ignored. (*note: SG refers to the standard group; CG1/2 refer to Control Group 1/2.)

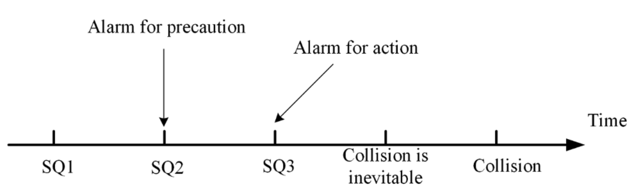

Fig. 9. The illustration of the timeline of alarms and collision event.

(the red and yellow region).

In brief, the additional ship would increase the collision risk in most case, while there are two cases that the additional ship would not increase the TCR level. Firstly, when the additional TS can be avoided by avoiding the existing TSs, i.e., the dangerous set generated by the new TS is the subset of the original dangerous set, the TCR level remains the same. Moreover, when the dangerous set of the introduced TS is out of the reachable set of the OS, the TCR level would not increase. Based on these findings, we conclude the Remark 2.

Remark 2: Collision risk would not be reduced when the ship encounters with one more ship.

4.4. Changes of risk due to the improvement of maneuverability

Many traditional methods ignored the conflict resolution in risk assessment. Thus, the measures using those methods cannot reflect the improvement/change of safety when the maneuverability of the ship is improved, and how does the risk be underestimated.

The maneuverability of the ship usually refers to turning ability, course-keeping ability, stopping ability, etc. (Liu et al., 2015). Here, the turning ability and stopping ability are focused.

An indicator shows the ability of turning is a tactical diameter that is the diameter of the turning circle, noted as $D_{turn} = 2R_{turn}$. A better turning ability has a smaller turning radius, which implies a bigger yaw-rate and torque. In other words, the ship with a better turning ability can generate a larger torque τ_r, i.e., the range of torque is larger. Head reach is a popular indicator to show the stopping ability, which is defined as the distance traveled in the direction of the ship's initial course in stopping trials. A shorter head reach requires a larger surge force. Thus, the ship with a good stopping ability can generate larger surge forces, i.e., a larger range of surge force τ_u.

In brief, better maneuverability implies the ship can generate a larger force in each direction, i.e., a bigger boundary of force range in Eq. (11).

To show the risk changes due to maneuverability, we carry out three groups of simulations. The setting of the Standard Group is the same as simulations in Section 4.3. Details are presented in Table 5. In Control Group 1, the maneuverability of the ship is improved, and the ship can produce 30% more forces than that in Standard Group. In Control Group 2, the ship only produces 70% forces. The settings have been presented in Table 5.

The control space of the OS in these groups has been presented in Fig. 7. Panel (2) is the result of the Standard Group, and the Panel (3)–(4) are from Control Group 1 (left) and Control Group 2 (right). The presented windows in these panels are the reachable set. In Standard Group, the maximal change of heading is ± 57° and the range of speed change is from −1 to 0.93 [knots]. By improving the maneuverability of the ship, the maximal changes of heading enlarge to ± 74° and the range of speed is in (-1.30, 1.23) [knot]. By reducing the maneuverability, the ranges shrink to ± 40° and (−0.72,0.64) [knot]. The TCR levels in these groups are 0.48, 0.37, and 0.66, respectively. According to this result, we find that poor maneuverability (Control Group 2) results in high collision risk and better maneuverability reduces the collision risk.

Additionally, if the ship maneuverability is ignored in risk assessment, such as in many existing collision risk measures, how does the risk level change?

To answer this question, we set the force boundary of the OS in Table 5 to be infinitely large. So, the ship can obtain relevant velocity immediately. The control space, then, is updated and presented in Fig. 8 where the change of speed ranges from (-10, 10) [knot], i.e., completely stop to the full ahead, and the change of the course ranges from (−90, 90) [°]. With these changes, the TCR is 0.16, which is quite low. However, in practice, the ship rarely can obtain such perfect maneuverability. Therefore, we conclude the Remark 3.

Remark 3: When two ships have conflict, the ignorance of ship maneuverability in collision risk assessment would underestimate the collision risk.

5. Discussion

In this section, the results and findings of simulations are concluded, together with discussions on the TCR measure and its applications.

5.1. Findings from the simulations

(1) Using DCPA, TCPA, and d_{ij} to assess the collision risk for conflict detection is insufficient.

In Section 4.2, we show that the risk measure independent of conflict resolution might not suitable for triggering evasive actions, i.e., SQ3. We simulate the encounters with identical values of DCPA, TCPA, and d_{ij}. Thus, the risk levels are seen to be the same by using DCPA, TCPA, and d_{ij} to assess collision risk. However, as we presented in Fig. 4, the chances for successfully avoiding collision are different. In some cases, the ship might merely find a collision-free solution or even no collision-free solutions (inevitably violates the safety region). In these cases, the collision risk should be higher than the others. However, the DCPA, TCPA, and d_{ij} indicators could not identify the difference. Thus, we conclude these indicators are insufficient for triggering evasive actions, i.e., SQ3 in Section 1.

Additionally, since the risk value calculated via existing measures is independent of conflict resolution, we also question the rationality of using the existing measure for SQ2, i.e., attracting the attention of the navigators. In our opinion, there is a chronology of alarms and collision events, which is shown in Fig. 9. The collision candidates need to be detected (SQ1) before the system can decide whether the approaching ship needs attention or not (SQ2). The navigators/systems need to be aware of dangers (SQ2) before they can take actions (SQ3). Hence, the collision warning for attracting the attention (i.e., SQ2) needs to be triggered not later than the collision becomes inevitable. However, since the existing risk measure is independent of conflict resolution, there is no guarantee that the SQ2 event (alarm for attracting attention) is always earlier than the collision becomes inevitable. Hence, if we use the existing methods for precaution, i.e., solving SQ2, the alarm failure (alarm too late) is inevitable.

In our opinion, one possible solution is incorporating the indicator associating to conflict resolution (i.e., the proposed TCR) in some existing risk measures framework (e.g., (Goerlandt et al., 2015), etc.).

(2) The TCR measure is suitable for assessing collision risk in multiple-encounter case.

Evaluation of the entire collision risk of the OS encountering multiple ships is one challenge for most existing measures. In fact, given the collision risk in each pair, how the value of the entire collision risk (from the perspective of the OS) is calculated has not had a unique answer.

Three possible operations are the maximum operation that uses the maximal risk to represent the entire risk, the summation that sums the risk in each pair to reflect the entire risk, and the average operation that uses the arithmetic mean to measure the entire risk. These methods have the following problems:

– The maximum operation ignores the approaching ships that are sub-dangerous, which might underestimate the entire collision risk of multiple-encounter scenario.
– Summation operation suggests that the dangerous level of the OS encountering with an emergent danger can be equal to that of the OS encountering with many not dangerous TSs. That means it might overestimate the collision risk when the ship encounters with multiple ships.
– The average operation suggests that the collision risk would be reduced when the OS encounters one more ship, that is not compliant with common ground.

The proposed TCR does not divide the ship traffic into pairs and assess the collision risk directly, which is suitable for assessing the collision risk of multiple-encounter.

(3) Ignorance of ship maneuverabilityresults in an underestimation of collision risk.

Many traditional risk measures ignored the ship maneuverability in collision risk assessment. However, naval architecture engineers believe that the improvement of ship maneuverability would improve the safety of the ship. By simulations in Section 4.4, the proposed TCR measure directly shows how does the improved maneuverability reduce the collision risk. On the other hand, we also observe that the ignorance of the constraints on maneuverability in a conflict would result in an underestimation of collision risk.

5.2. TCR and its applications at sea

TCR levels reflect the percentages of collision-free solutions for the OS, which is also noted as the room-for-maneuver or maneuvering margin. A higher TCR implies that the OS has more freedom in choosing a collision-free solution. Thus, a lower chance to strike the TS. On the opposite, a lower TCR means the OS has less freedom in taking evasive actions.

Moreover, one needs to be aware that the calculation of TCR measure incorporates the ship dynamics and controllers. Thus, the TCR level is dependent on the settings of the PD controller. For instance, when the TCR reaches 1, it basically means the collision is inevitable by the OS with the designed controller. That means, in this case, human operators on the OS still can avoid collision by changing the setting of its controller, e.g., change the feedback gains, choose other types of controller, etc. However, if the operators cannot change their controllers, the cooperation with the TS would be necessary for avoiding collision.

This risk measure is developed to support the navigators to take actions before it would be too late. A potential application can combine with the Collision Avoidance System (CAS) presented in (Huang et al., 2019) in which the GVO algorithm is also used to find a collision-free solution automatically. The navigators or human controllers of MASS can freely postpone the evasive actions suggested by the CAS until the TCR reaches 1. Before the TCR reaches 1, the human operators still can use the solution suggested by the CAS to avoid collision. After the TCR reaches 1, the human operators either adjust the settings of PD controllers or cooperate with TSs to avoid collisions. Another application can ben found in Du (2020), where the idea of TCR measure is expanded to support the stand-on ship to judge the intention of give-way ships based on COLREGs.

6. Conclusion

In this article, three main tasks of conflict detection for various collision avoidance/alert system (CAS) in manned ships and unmanned ships are concluded, including identifying collision candidates, sending precaution in time, and triggering evasive action in time. By comparing existing measures, we found that most of them might result in failures due to the ignorance of conflict resolution and dividing the traffic into pairs in the risk measure. To handle these issues, Time-varying Collision Risk (TCR) proposed in (Huang and van Gelder (2020) has been improved in this article by considering ship dynamics and various constraints.

Simulations are designed to compare the improved TCR with popular risk measures, e.g., Collision Risk Index (CRI). The results show that the same values of Distance to CPA (DCPA), Time to CPA (TCPA), and relative distance do not mean the same level of collision risk. It reveals that these indicators alone are insufficient for setting off alarms for precaution and timely evasive actions, and the indicator associates to conflict resolution (i.e., TCR) would be a useful and necessary supplement to the traditional risk measures. Firstly, the traditional measure cannot help the own-ship (OS) to assess the entire collision risk in a multiple encounter situation, whereas the proposed TCR measure can fill the gap. As shown in the simulation, collision risk would not reduce when the OS encounters with one more target ship. Secondly, the TCR measure shows that the improvement of maneuverability reduces collision risk and ignorance of maneuverability leads to an underestimation of collision risk. The proposed TCR measure can be embedded in navigational assistance systems to support the navigator onboard or the human operator in the offshore center to take timely evasive action.

Further research is needed for improving the proposed measure. Firstly, some assumptions are made to simplify the calculation of the TCR measure, such as deterministic and known the dynamic of the OS and semi-dynamic movement of the TS[1]. Hence, using the improved TCR measure in an arbitrary ship in practice needs further studies. Nevertheless, it is enough to demonstrate the limitations of some popular collision risk measures. Secondly, the calculation of TCR is based on the specific design of the controllers. As we discussed in Section 5.2, the value of TCR is based on the designed controllers. If the TCR reaches 1, it does not mean that the collision is inevitable by all means. To calculate the TCR level regardless of specific settings of controllers, reachability analysis would be needed in the future. Thirdly, the

[1] Semi-dynamic movement refers to the movement that keeps speed and course.

proposed TCR measure ignores the influences of the regulations, such as COLREGs. In the measure of TCR, the regulations are temporarily ignored since the main purpose of this article is to find the limitations of the existing methods. In fact, incorporating COLREGs is possible by reconstructing the reachable set in Section 3.2.3. Specifically, the rules from COLREGs can be interpreted as the extra constraints on the reachable sets. For instance, when the OS is the give-way ship, the ship is not suggested to steer to its port for avoiding collision. Thus, we can block the maneuvers in the right half-plane of the reachable sets.

Appendix A

See Tables A1–A3.

Table A1
Overview of Collision Risk Index methods.

Formulations	Brief descriptions	References
$CRI_1 = w_1 f(DCPA) + w_2 f(TCPA)$	DCPA and TCPA are combined in a linear equation.	Chin and Debnath (2009), Kearon (1979), Lee and Rhee (2001)
$CRI_2 = \sum_i w_i f_i(RI_i) / \sum_i w_i$	DCPA, TCPA, and other factors are combined in a linear equation.	Ahn et al. (2012), Baldauf et al. (2011), Bukhari et al. (2013), Gang et al. (2016), Goerlandt et al. (2015), Li and Pang (2013), Lopez-Santander and Lawry (2016), Zhao et al. (2016)
$CRI_3 = \left[w_1\left(\frac{DCPA}{d_s}\right)^2 + w_2\left(\frac{TCPA}{T_s}\right)^2 + w_3\left(\frac{d_{ij}}{d_s}\right)^2\right]^{-\frac{1}{2}}$	DCPA, TCPA, and relative distance are used to measure the Euclidean distance.	Lisowski (2002), Szlapczynski (2006)
$CRI_4 = r_{basic} e^{-TCPA/10} e^{-\lvert DCPA \rvert} . F_{angle}$	DCPA, TCPA, angles, and frequency of collision events are combined nonlinearly.	Ren et al. (2011), Szlapczynski (2006)
$CRI_5 = \cos(v_{ij}, d_{ij}) = \frac{v_{ij} d_{ij}}{\lVert d_{ij} \rVert \lVert v_{ij} \rVert}$	The angle between v_{ij} and d_{ij} is used to describe the trend of relative movement.	Perera and Guedes Soares (2015), Wen et al. (2015)
$CRI_6 = k d_{ij}^{-1} v_{ij} (m \sin(\theta_{ij}) + n \sin(2\theta_{ij}))$	v_{ij}, d_{ij}, and encounter angle are combined using supervised learning methods.	Zhang et al. (2015a), Zhang et al. (2015b)
Other forms (risk table)	Using a risk table to determine CRI.	Hilgert and Baldauf (1997), Ożoga and Montewka (2018), Perera et al. (2011)

Table A2
Overview of three modes of warning ring by ship domain.

Name	Measuring methods	References
WR-SD1	Comparing the predicted trajectory of one ship with the other ship's domain. The alarm is triggered when the domain will be violated.	Pietrzykowski (2008), Tam and Bucknall (2010) Zhao et al. (1994), Zhao et al. (1993)
WR-SD2	Comparing the position of one ship with the other ship's domain, e.g., quaternion ship domain, ship arena, etc. The alarm is triggered when the expanded domain is violating	Colley et al. (1983), Davis et al. (1980), Wang (2012)
WR-SD3	The overlapping of ship domains indicates the risk level. The alarm is triggered when the overlapping domains satisfying certain criteria.	Kao et al. (2006), Kijima and Furukawa (2003)

Note: WR-SD refers to methods using ship domain in conflict detection, and the index 1, 2, 3 refer to three modes of using ship domain in conflict detection.

Table A3
Details of studies working on conflict detection.

	Prediction of the TS			Conflict Detection				Remarks	Application
	Assumption	Model	Uncertainty	Candidates Detection	Collision Alert	Trigger actions	COLREGs		
Chin and Debnath (2009)	Semi-dyna.	–	–	CRI_1	CRI_1	CRI_1	–	Ordered Probit Model; learning from experts (pilots); 5 risk levels.	OOW
Debnath and Chin (2010)	Semi-dyna.	–	–	CRI_1	CRI_1	CRI_1	–	Ordered Probit Model; learning from conflict data; validated by pilots; 5 risk levels.	OOW
Gang et al. (2016)	Semi-dyna.	–	–	CRI_2	CRI_2	CRI_2	√√	CRI = *f*(DCPA,TCPA, dij, angles, velocity ratio);SVM is employed to determine the weights. 3 risk levels, which can be adjusted.	OOW
Li and Pang (2013)	Semi-dyna.	–	–	CRI_2	–	–	√√	CRI = *f*(DCPA,TCPA, dij); D-S evidence theory.	OOW
Ahn et al. (2012)	Semi-dyna.	–	–	CRI_2	CRI2*	CRI_2*	√	Neural network and Fuzzy interfere; CRI = *f*(DCPA,TCPA, ship domain, multi factors)	OOW
Bukhari et al. (2013)	Semi-dyna.	–	–	CRI_2	CRI_2*	–	–	Fuzzy interfere system is used; CRI = *f*(DCPA,TCPA, change on relative bearing). Risk is ranged [-1,1];	VTSO
Goerlandt et al. (2015)	Semi-dyna.	–	–	CRI_2	CRI_2	–	√√√	Fuzzy theory; Experts are involved in the determination of weights and validations; Incorporating COLREGs in detail. 4 risk levels.	OOW
Lopez-Santander and Lawry (2016)	Predictable by KF	1	√	CRI_2	CRI_2*	–	√√	Ordered Probit Model; Questionnaires to determine the weights; considering COLREGs; The threshold of collision alert is missing.	OOW
Lisowski (2014)	Semi-dyna.	–	–	–	–	CRI3	–	CRI = *f*(DCPA,TCPA, dij); the OS take reactive actions when risk is not 0;	ASV
Mou et al. (2010), Ren et al. (2011)	Semi-dyna.	–	–	CRI_4	CRI_4*	–	–	CRI = *f*(DCPA, TCPA, angles, basic risk). Considering the average collision risk in certain waters.	OOW
Perera and Guedes Soares (2015)	Predictable by EKF	1	√	CRI_5	–	–	–	CRI = *f*(d_{ij},v_{ij}); severity levels for triggering actions and alert are not determined in this paper.	ASV
Wen et al. (2015)	Semi-dyna.	–	–	CRI_5	CRI_5	–	√√	CRI = *f*(conflict factor, density factor), conflict factor use CRI_5 model. The final index is called complexity. Thresholds are determined by VTSO.	VTSO
Zhang et al. (2015b)	Semi-dyna.	–	–	CRI_6	–	–	–	CRI = *f*(d_{ij}, $angle_{ij}$, v_{ij}), also known as Vessel Conflict Ranking Operator (VCRO); Supervised learning method; Rank the danger levels of the TSs.	OOW
Zhang et al. (2016)	Semi-dyna.	–	–	CRI_6	–	–	–	CRI = *f*(d_{ij}, $angle_{ij}$, v_{ij}), or VCRO. Supervised learning method; Ship domain is introduced.	OOW
Zhang et al. (2017)	Semi-dyna.	–	–	CRI_6	CRI *	CRI *	–	CRI = *f*(*VCRO*, Δ*VCRO*, ship size), or VCRO. Supervised learning; Ship domain is introduced; Fuzzy logic is used to categorize the risk in 5 levels.	OOW
Szłapczyński and Śmierzchalski (2009) DR-Vspace: CTPA; the OS take action when velocity is in CTPA.	Semi-dyna. OOW	–	–	CRI	–	DR-Vspace	–	CRI uses a different form of formulation, *f*(DCPA,TCPA, dij);	
Kao et al. (2006)	Semi-dyna.	–	–	CRI	WR-SD3	–	–	CRI uses a different form of formulation and is named as a danger, *f*(time to collision); Ship domain is used for collision alert.	VTSO
Baldauf et al. (2011)	Semi-dyna.	–	–	CRI*	CRI *	CRI*	√√	CRI: Instead of using a formulation, this study using a pre-set matrix table to determine CRI value. Inputs are DCPA and relative distance.	OOW
Ożoga and Montewka (2018)	Semi-dyna.	–	–	CRI	CRI	CRI	√√	CRI: Instead of using a formulation, this study using a pre-set matrix table to determine CRI value. Inputs are DCPA and TCPA.	OOW
Su et al. (2012)	Semi-dyna.	–	–	–	–	DR-Wspace	√√	A fuzzy collision danger domain is used. The size of the danger domain is adapted according to sea state, ship's speed, and ship size.	VTSO
Pietrzykowski (2008), Pietrzykowski and Uriasz (2008)	Semi-dyna.	–	–	WR-SD1	–	–	–	Dynamic Fuzzy SD adapted to different configurations of TSs.	OOW
Wang (2010, 2012)	Semi-dyna.	–	–	WR-SD2	–	–	√	Quaternion ship domain is proposed to comply with COLREGs and to consider the maneuverability;	OOW
Perera et al. (2011), Perera et al. (2012)	Semi-dyna.	–	–	WR-SD2	WR-SD2	CRI	√	WR-SD2: the risk is determined by the position of the TS. The ring is categorized into several sections according to CORLEGs. The trigger of action is according to a pre-set matrix using Fuzzy-Bayesian method.	ASV
Kijima and Furukawa (2003)	Semi-dyna.	–	–	WR-SD3	WR-SD3	WR-SD3	–	Choose one collision-free solution from three pre-set solutions. SD is modified by maneuverability of the OS. Evasive action and alert are triggered when overlap.	ASV
Woerner et al. (2018)	Semi-dyna.	–	–	DCPA	CRI	–	√√√	A safety score is used to determine risk level, which is similar to CRI methods but different formulation from $CRI_{1\sim6}$. 4 warning levels.	OOW /ASV

(*continued on next page*)

Table A3 (*continued*)

	Prediction of the TS			Conflict Detection				Remarks	Application
	Assumption	Model	Uncertainty	Candidates Detection	Collision Alert	Trigger actions	COLREGs		
(Park & Kim, 2016)	Keep velocity	1	√	P_{coll}	–	P_{coll}	–	P_{coll}: a probabilistic risk map of maneuvers are presented, which is based on the estimation of probability in each maneuver candidates. The detection process ignores the COLREGs.	OOW
Tam and Bucknall (2010)	Rule-compliant	3	–	DR-Wspace	–	DR-Wspace	√	DR-Wspace: The safety area of the TS is posted around the position of TS instead of CPA, which is a region the OS should not avoid.	OOW
Smierzchalski and Michalewicz (2000)	Semi-dyna.	–	–	DR-Wspace	–	DR-Wspace	–	DR-Wspace: PAD located at the joint point of trajectories of the OS and the TS. When the PAD is violated, evasive action is triggered. Ship domain is shaped as a hexagon.	OOW
Fukuto and Imazu (2013)	Semi-dyna.	–	–	DR-Wspace	DR-Wspace	DR-Wspace	–	DR-Wspace: OZT. Alert and evasive action are triggered when the course of the OS cross OZT. Cannot rank the danger levels.	OOW
Kayano and Kumagai (2017)	Known Waypoints	3	–	DR-Wspace	–	DR-Wspace	–	Idem, but the rule of alert is not mentioned. This paper also discussed the mental load of using different modes of OZT.	OOW
Szlapczynski and Szlapczynska (2015)	Semi-dyna.	–	–	–	–	DR-Vspace	–	DR-Vspace: CTPA; the OS takes action when velocity is in CTPA and ship domain is incorporated.	OOW
Szlapczynski and Szlapczynska (2017)	Semi-dyna.	–	–	–	–	DR-Vspace	–	DR-Vspace: CTPA; the OS take action when velocity is in CTPA; ship domain is incorporated; restrict water is taken into account.	OOW
Szlapczynski and Krata (2018)	Semi-dyna.	–	–	–	–	DR-Vspace	–	Idem; Hash environment and maneuverability are considered.	OOW
Krata and Montewka (2015)	Semi-dyna.	–	–	–	–	Action Lines	–	It is also named as critical envelope. The Action line in crossing scenario is showed.	OOW
Szlapczynski et al. (2018)	Semi-dyna.	–	–	–	–	Action Lines	√√√	Demonstrate action lines in different encounter scenarios.	OOW
Baldauf et al. (2017)	Semi-dyna.	–	–	–	–	Action Lines	–	The method is named as: last line of defense (LLOD). The construction of LLOD was using a ship simulator assigning a max rudder angle to the OS.	OOW

Note: (1) In Prediction columns: Semi-dyna.: semi-dynamic, which is refers to the TS is assumed to sail with constant speed and course; Mode "-": the TS is assumed to be constant speed and course; Mode 1: the trajectory of the TS is estimated by the OS following physical law; Mode 2: the trajectory of the TS is estimated by the OS considering estimated intention; Mode 3: the trajectory of the TS is known by communication.
(2) In Detection columns: DR-Wspace refers to Dangerous Region using Workspace; DR-Vspace means to use the Dangerous Region in Velocity space to judge collision dangers.
(3) In Detection columns: if the study did not mention the settings of thresholds of alert or of evasive action, we add "*" at the end, means "No Thresholds". In COLREGs column, √: the COLREGs is incorporating in the measure by rule-compliant ship domain; √√: the COLREGs is used to separate different scenarios and train the weights of models; √√√: means the measure is reconstructed for different scenarios (different factors, etc.) even the framework is not changed.
(4) Application column indicate the developed the risk measures are served for: OOW, officer on watch; VTSO, VTS operator; ASV, Autonomous surface ship.

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