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Measuring Ship Collision Risk in a Dense Traffic Environment

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ABSTRACT: Collision risk measurement is an essential topic for ship collision prevention. Many risk measures, i.e. DCPA/TCPA, etc., decouple the ship traffic into several pairs of ships and then evaluate the risk in each pair. This kind of measurement loses some information of the entire traffic and might include some biases in risk measurement, especially in multiple-ship scenarios. In this article, Imminent Collision Risk Assessment (ICRA) is extended, which formulates collision risk as a ratio of reachable maneuvers leading to a collision and all reachable maneuvers (velocities). Two groups of scenarios have been simulated to show the ICRA is suitable for assessing the collision risk in multiple-ship scenarios. Moreover, two improvements have been introduced: (1) a generalized velocity obstacle algorithm is introduced to collect the maneuvers leading to collisions, which considers ship dynamics; (2) the constraints of forces are considered in the formulation of reachable maneuvers. As a result, the proposed measurement helps one ship assess the risk of approaching obstacles which are difficult to avoid the collision in terms of own-ship's dynamics and kinetic constraints.

1 INTRODUCTION

Risk metrics are important for collision prevention at sea. When one ship encounters with obstacles, the Officer On Watch (OOW) needs to appraisal the dangerous levels of these obstacles for decision making, e.g. continue with current operations or take new actions. The importance of risk metrics is also stipulated in international regulations for prevention collision at sea (COLREGs), which requests the OOWs to "make a full appraisal of the situation and of the risk of collision" (Organization), 1972). Hence, various collision risk metrics have been developed and proposed in past decades and these metrics have become the core of various collision alert systems (Goerlandt, Montewka, Kuzmin, & Kujala, 2015) and automatic collision avoidance systems (Johansen, Perez, & Cristofaro, 2016).

Most of the collision risk metrics usually choose a pair of ships from traffic to evaluate the risk. In each pair, the ship under our control is usually called own ship (OS) and the other is target ship (TS). By choosing different TSs, different pairs of ships are obtained and the collision risk in each pair is evaluated. That means the ship out of the pair is temperately ignored. Researchers use numerous indicators to calculate the collision risk which is also named as collision risk index (CRI). In these indicators, two frequently used ones are Distance to Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA). By this approach, the OOWs can calculate the CRI of each TS, find the TS in conflict with the OS (whose CRI over the threshold), and identify the most dangerous TS.

This group of methods, however, have difficulties in showing the entire risk level of the traffic for the OS when the OS encounters with multiple ships. In technique level, there are no agreements on combining various CRIs into one number which represents the risk of the entire traffic. There are some alternatives, such as average, sum, and maximum, while they more or less have some drawbacks. The "average" underestimates the most dangerous TS; the "maximum" ignores the influence from non-conflicting TSs; the "sum" offers limited information about collision event in each pair.

Furthermore, when we decouple the traffic in several pairs of ships, we lose some information about traffic and introduce some biases in collision risk assessment. 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, it might block some operations of the OS which might result in an inevitable encounter between the OS and another TS; (2) the risk caused by traffic characteristics is ignored. For example, the CRI value in each pair of ships are the same, but well-organized traffic seems to be safer than others (see Section 3.2 for details).

This paper offers a new perspective to evaluate the collision risk for the OS, which considers all the target ships together. The risk measurement presented in literature (Y. Huang, Gelder, & Mendel, 2016) and (Y. Huang & van Gelder, 2019) is applied to multiple-ship cases, which is named as Immediate Collision Risk Assessment (ICRA) in this paper. Moreover, based on the original ICRA, the ship's dynamics and constraints on forces are considered. The structure of this paper is as follows: the background and gaps of existing collision risk assessment are presented in this section; the details of ICRA and the improved ICRA are shown in Section 2; Section 3 collects three groups of scenarios which show the performance of ICRA and improved ICRA; at the end, discussion and conclusion are presented in Section 4 and Section 5, respectively.

2 COLLISION RISK MEASUREMENT

2.1 *Immediate Collision Risk Assessment Method*

Immediate collision risk assessment (ICRA) (Y. Huang et al., 2016) measures the collision risk with the aid of "room-for-maneuver" (Degre & Lefevre, 1981). In (Y. Huang & van Gelder, 2019), this concept is further developed. The construction of the ICRA follows some steps: firstly, the encounter scenarios have been projected from geography space into velocity space (**V-space**) and the velocities leading to collision are collected in Velocity Obstacle (VO) set; secondly, a set of velocities that one ship can achieve is denoted as reachable velocity (RV) set; lastly, the overlap of VO set and RV set are the reachable velocity leading to collision and the collision risk is measured by the percentage of the overlap, i.e.:

$$ICRA = \frac{S(\mathrm{VO} \cap \mathrm{RV})}{S(\mathrm{RV})}, \quad (1)$$

where $S(\bullet)$ represents an operation that calculates the area of the inputted polygon, e.g. $S(\mathrm{RV})$ is the area of RV set; $\mathrm{VO} \cap \mathrm{RV}$ represents the overlap of VO set and RV set, as shown in Fig. 1.

The formulation of VO set is relying on velocity obstacle algorithm. In some maritime studies, this algorithm is also named as Collision Threat Parameter Area (CTPA) (Lenart, 1983; Szlapczynski & Krata, 2018) or Collision Danger Sector (CDS)(Pedersen, Inoue, & Tsugane, 2003). Readers who are interested in this algorithm can read more in the literature (Fiorini & Shiller, 1998) and its applications in maritime studies can be found in (Y. M. Huang, van Gelder, & Wen, 2018) and (P. Chen, Huang, Mou, & van Gelder, 2018). The construction of RV set is related with time to collision and maneuverability of the ship. For the sake of simplification, some researchers use constant maximal speed and instantaneous heading changes to construct the RV set (Westrenen & Ellerbroek, 2017).

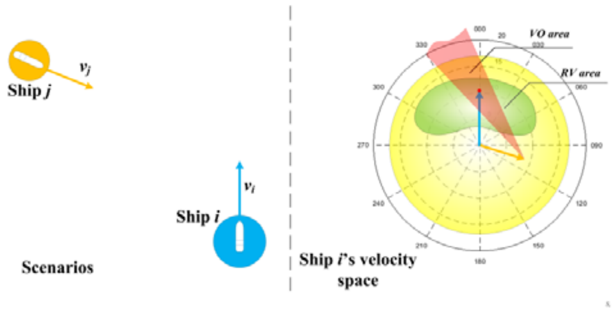


Figure 1 The illustration of ICRA measurement

In this paper, we employed the VO algorithm proposed in the literature (Fiorini & Shiller, 1998), in which the target-ship is assumed to keep the constant speed and course. The RV set is simplified as the half of the whole V-space of the OS, i.e. velocity in surge direction accepts $v_u \in [0, v_{\max}]$ and velocity in sway direction is $v_v \in [-v_{\max}, v_{\max}]$. One example is shown in Fig. 3 (2).

2.2 *Improved ICRA*

In the previous section, the constructions of VO set and RV set accept some simplifications. Specifically, the ship's dynamics is ignored and the RV set is simply equal to the half of V-space. However, these simplifications influence the performance of I-ICRA measurement in close range. For example, the in close range, the many collision-free solutions, i.e. $v \in \mathrm{VO} \cap \mathrm{RV}$, are not reachable regarding ship's dynamics.

To solve this problem, we use generalized velocity obstacle (GVO) to collect the velocity set leading to collisions, which was proposed in the literature (Bareiss & van den Berg, 2015) and applied to ship collision avoidance in the literature (Y. M. Huang, Chen, & van Gelder, 2019).

2.2.1 *The motion model of the ship using velocity as the input*

The ship dynamics model used in this paper is from literature (Fossen, 2002). $\mathbf{x}$ and $\boldsymbol{\tau}$ denote states of the ship and inputted forces. $\mathbf{x}$ consists of the position of the ship, heading, surge speed, sway speed and yaw rate, i.e. $[x, y, \psi, u, v, r]^{\mathrm{T}}$. The inputted forces will modify the states of the ship, see Fig. 2 (1).

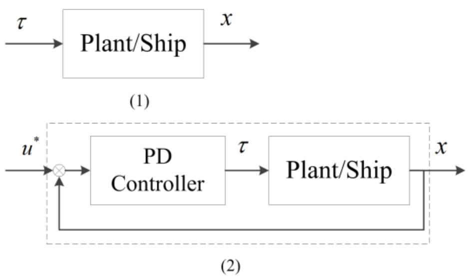


Figure 2. Set the desired velocity **u*** as inputs to the system.

Since the VO set collects velocities instead of forces, we introduce a PD controller to switch the input from forces to the desired velocity noted as **u***, see Fig. 2 (2). The control is formulated as:

$$\tau = K_p\left(\mathbf{u}^* - \mathrm{V}\mathbf{x}\right) - K_d \mathrm{V}\dot{\mathbf{x}}, \tag{2}$$

here, K_p and K_d are feedback matrices; **u*** is desired velocity contains the desired surge speed, sway speed, and heading. In return, we have a new motion model:

$$\left(\begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{M}\end{bmatrix} + \mathrm{BK_d V}\right)\dot{\mathbf{x}} = \begin{bmatrix}\mathbf{R}(\psi)\mathbf{v}\\ -\mathbf{C}(\mathbf{v})\mathbf{v} - \mathbf{D}(\mathbf{v})\mathbf{v} - \mathrm{K_p V}\mathbf{x}\end{bmatrix} + \mathrm{BK_p}\mathbf{u}^*, \tag{3}$$

here, $\mathbf{v} = [u, v, r]^{\mathrm{T}}$ is velocity states; **C**(**v**), **D**(**v**), **M**, and **R** are Coriolis, damping, mass, and rotation matrices, respectively; **I** is a 3-by-3 identical matrix and $\mathrm{B} = \left[\mathbf{0}^{3\times3}, \mathbf{I}^{3\times3}\right]^{\mathrm{T}}$. This equation can also be rewritten in a general form:

$$\dot{\mathbf{x}} = f\left(x, u^*\right) = f_1\left(x, K_p, K_d\right) + f_2\left(x, K_p, K_d\right)u^*, \tag{4}$$

where $f(\bullet)$ is nonlinear.

2.2.2 *The desired velocity leading to a collision*

Firstly, we define the collision event at time *t* as an event that one ship violates a minimum safety region of the other ship at time *t*, which is formulated as:

$$P_i(t) \in P_j(t) \oplus ConfP, \tag{5}$$

P_i and P_j are the position of the OS and the TS; *ConfP* is the minimum safety region; $P_j(t) \oplus ConfP$ is a set of safety region surrounding the target ship.

Secondly, we formulate the relation between P_i and **u*** in the help of a linearization of equation (4) around its initial state $\boldsymbol{x}^0$ and initial input $\boldsymbol{u}^0$:

$$\mathbf{x}_i(t) \approx \tilde{\mathbf{x}}_i(t) + G(t)\left(\mathbf{u}^* - \mathbf{u}^0\right), \tag{6}$$

where G is a response matrix; $\tilde{\mathbf{x}}_i(t)$ is the trajectory of the OS given the initial state and inputs, which is calculated via Runge-Kutta Integration. Since we only need the position of the OS, we introduce a matrix C, which:

$$\begin{aligned} P_i(t) &= C\mathbf{x}_i(t) \approx C\tilde{\mathbf{x}}_i(t) + CG(t)\left(\mathbf{u}^* - \mathbf{u}^0\right)\\ &= \tilde{P}_i(t) + CG(t)\left(\mathbf{u}^* - \mathbf{u}^0\right) \end{aligned}, \tag{7}$$

here, $\tilde{P}_i(t)$ is the estimated trajectory of the OS with initial input $\boldsymbol{u}^0$.

Thirdly, we substitute Equation (7) to Equation (5) and formulate the changes on inputs leading to collision:

$$\left(\mathbf{u}^* - \mathbf{u}^0\right) \in (CG)^{-1}\left\{\left(P_j(t) - \tilde{P}_i(t)\right) \oplus ConfP\right\} = \mathrm{sUO}(t). \tag{8}$$

This set only collects **u*** resulting in a collision at time *t*. Thus, if we sum the $\mathrm{sUO}(t)$ that $\forall t \in (0, \infty]$, we obtain all **u*** leading to a collision in the future, which is named as UO set.

$$\left(\mathbf{u}^* - \mathbf{u}^0\right) \in \bigcup_{t=0}^{\infty} \mathrm{sUO}(t) = \mathrm{UO}.$$

2.2.3 *Considering constraints on forces.*

In Section 2.2.2, we collect the velocity that leading to a collision in the future, while, not all the velocity out of this set are reachable for the ship regarding its dynamics and constraints. For instance, one ship might not generate enough powers to achieve the desired velocity. Hence, in this section, the constraints on forces are considered.

Let say, the force in each direction is satisfying constraints:

$$\boldsymbol{\tau}_{\mathbf{lb}} \le \boldsymbol{\tau} \le \boldsymbol{\tau}_{\mathbf{ub}}. \tag{9}$$

Then, we can formulate the forces as a function of the states and the desired velocity according to Equation (3) and Equation (2), i.e.:

$$\boldsymbol{\tau} = \left(K_p - K_d V f_2\right)\mathbf{u}^* - \left(K_p V\mathbf{x} - K_d V f_1\right). \tag{10}$$

Combining Equation (9) and (10), we derive the constraints on the desired velocity **u***:

$$\left(K_p - K_d V f_2\right)^{-1}\left(\boldsymbol{\tau}_{\mathbf{lb}} + K_p V\mathbf{x} - K_d V f_1\right) \le \mathbf{u}^* \le \left(K_p - K_d V f_2\right)^{-1}\left(\boldsymbol{\tau}_{\mathbf{ub}} + K_p V\mathbf{x} - K_d V f_1\right). \tag{11}$$

Equation (11) is the reachable velocity set satisfying the constraints on forces given a PD controller.

3 CASE STUDIES

Three groups of scenarios have been designed in this section. The performance of ICRA in multiple-ship encounters and different traffic modes are presented in Section 3.1 and Section 3.2, respectively. In Section 3.3, a demonstration of I-ICRA considering ship dynamics and constraints is shown.

3.1 *Performance of ICRA in multiple-ship scenarios*

Three encounter scenarios have been simulated to show the performance of the ICRA. In each scenario, the own-ship is placed at the origin heading to the North with speed at 10 knots, while the number of target ships is increasing from one to three. In the first scenario, the OS only encounters with one target-ship (TS1) whose DCPA is 0.5 [NM] and TCPA is 0.25 [h]. In the second scenario, one extra target-ship (TS2) is introduced and the DCPA and TCPA remain the same as that of the TS1. In the last scenario, the OS encounters with three target ships together, namely TS1, TS2, and TS3. The details of the settings are presented in Table 1.

Table 1. Settings of scenario

	Position [NM]	Heading [deg]	Speed [knot]	DCPA [NM]	TCPA [h]
Own Ship	(0,0)	000	10.0	-	-
TS1	(0.65,-1.44)	358	16.0	0.5	0.25
TS2	(-2.45,1.80)	081	8.5	0.5	0.25
TS3	(3.38,3.02)	268	14.7	0.5	0.25

In a two-ship scenario, the TS1 approaches the OS from its stern and the ship blocks the starboard-turn options of the OS, as shown in Fig. 3 (2). The blue area is the VO set which collects the velocity of the OS leading to a collision with the TS1. The rest of the area is collision-free for the OS, which also can be interpreted as the “room-for-maneuver”. According to Section 2.1, the percentage of the VO shows the danger level of the OS which is 0.749. That means, the ship still has 0.251 chance to avoid the collision.

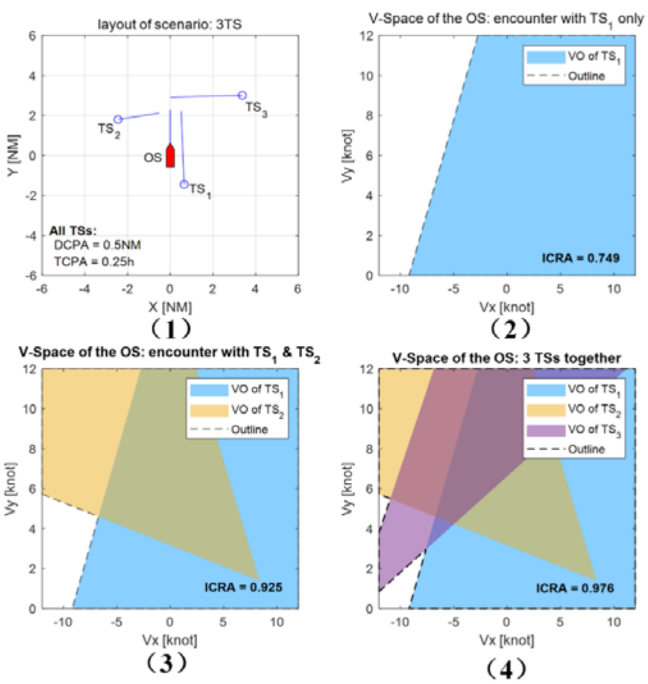


Figure 3 The V-Space of the OS when it encounters with one TS, two TSs and three TSs

When we introduce one more ship (TS2) whose DCPA and TCPA are the same as the that of TS1, the entire collision risk is undefined by traditional methods (CRI methods), especially the new ship has the same CRI with the TS1. As we can expect that more ships in the same area might increase the collision risk, but how do the new CRI influence the original CRI is unclear. ICRA offers a solution to this problem. One more ship blocks some extra “room-for-maneuver” which leads to less chance to avoid collision dangers, as shown in Fig. 3 (2). As a result, the encounter scenario would be more dangerous than the previous scenario. As we show, the ICRA, in this case, raises from 0.749 to 0.925, which means the number of solutions for the OS to avoid collision decrease and the OS is more dangerous than the previous case. When the OS encounters with three ships together, the area of “room-for-maneuver” is shrunk furthermore. When the whole velocity space is occupied by the VO sets, that means, the collision is inevitable in the future and the ICRA reaches 1.

3.2 *Well-organized traffic versus chaotic traffic*

In this section, the influence of ship traffic on the measurement of collision risk is shown. Three scenarios are simulated, in which three target ships are involved, namely TS1, TS2, and TS3. The same ship in different scenarios has the same DCPA, TCPA, and relative distance, while the position and velocity are slightly different. For example, the TS1 in each scenario has different positions and speeds, but the same settings of DCPA, TCPA, and relative distance.

In the first scenario, three ships are grouped as a vessel train (L. Y. Chen, Hopman, & Negenborn, 2018), specifically these vessels have the same velocity and keep the formation in purpose. In the second and the third scenarios, each target ship keeps its relative distance to the OS in the first scenario, but the bearings of each target ship are changed. In the second scenario, the bearing of the target ship is changed in a small angle, say an arbitrary angle smaller than 60 degrees (See Fig. 4); in the last scenario, the changing range is enlarged to 240 degrees. An illustration is shown in Fig. 4. The TS3 is located at Point A in the first scenario, while the TS3 is randomly located on the arc BC and DE in the second and third scenario respectively. The details of the settings are shown in Table 2.

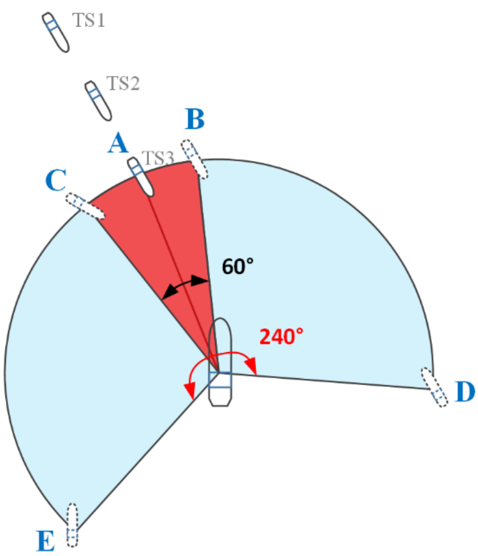
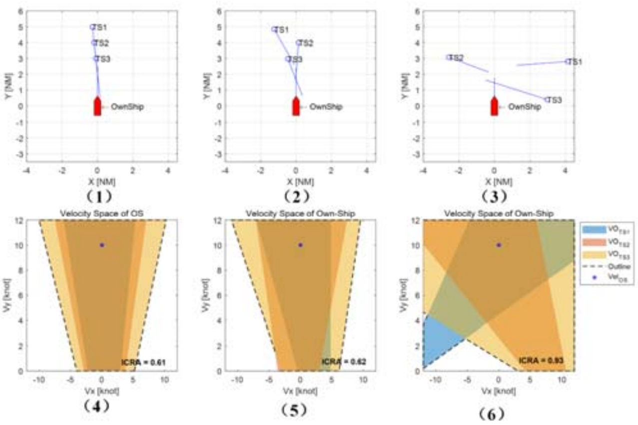


Figure 4. The illustration of the position of TS3 in three different scenarios

Table 2. Settings of scenarios

Case	Ship	Position [NM]	Heading [deg]	Speed [knot]	DCPA [NM]	TCPA [h]
	Own Ship	(0,0)	000	10.0	-	-
1	TS1	(-0.29,4.99)	174	10.0	0.05	0.25
	TS2	(-0.19,4.00)	174	10.0	0	0.20
	TS3	(-0.10,3.00)	174	10.0	0.05	0.15
2	TS1	(-1.23,4.84)	153	10.6	0.05	0.25
	TS2	(0.14,4.00)	184	10.0	0	0.20
	TS3	(-0.46,2.97)	161	10.1	0.05	0.15
3	TS1	(4.14,2.81)	265	16.5	0.05	0.25
	TS2	(-2.56,3.07)	112	13.9	0	0.20
	TS3	(2.98,0.40)	070	21.0	0.05	0.15



Figurer 5. the V-Space of the OS when it encounters with three ships in three cases, namely well-organized case, disorder case, and chaotic case. (the DCPA, TCPA and relative distance of one ship, e.g. TS1 in case 1, are as the same as the ship in other cases.)

Fig. 5 (1)-(3) show the layouts of each scenario and (4)-(6) show the V-space of the OS in relevant scenarios. The first scenario is a case that the traffic is well-organized; in the second scenario, the traffic is relatively disordered comparing with the first; in the last scenario, the traffic is considered to be a chaotic case.

The target ships have the same DCPA, TCPA and relative distance in these scenarios. That implies each pair in these scenarios has the same collision risk. Hence, we might conclude the collision risk in each scenario is the same. However, the OS in the last scenario seems more dangerous than the others because the OS might not easily find one collision-free solution.

ICRA can catch the difference in collision risk in these scenarios. The value of ICRA indicates the collision risk in these scenarios, which are 0.61, 0.62, and 0.93. The ICRA shows the difficulty of avoiding the collision in each case. Although the DCPA, TCPA, and relative distance are all the same in each scenario, the room-for-maneuvers are different in each scenario.

Three VO sets from three target-ships have been identified in each scenario. In the first scenario, traffic is well-organized and all these VO sets are containing in one VO set generated by TS3. That means, if the OS can avoid collision with the TS3, the ship can avoid collision with TS2 and TS1, as well. In the last scenario, each VO set blocks different groups of maneuvers. For instance, the collision-free solutions for avoiding TS3 (the bottom-left area) are blocked by TS1. That means, even if the solution can help the OS to avoid the TS3, it might not avoid collision with TS1. As a result, the collision danger is more difficult to reject and the collision risk is high.

3.3 *Demonstration of ICRA considering ship's dynamics*

In the previous scenarios, the maneuverability of the ship is ignored and the ship is enabled to change its velocity immediately. However, the real ship has various constraints in kinematic and dynamics. For example, the ship has maximal speed, maximal turning rate, maximal thrust, etc.

In this scenario, the dynamic model of the ship is considered. The ship model called "CyberShip II" is considered to be the OS, which is a 1: 70 small scaled marine surface vehicle model. The mass of this ship model is 23.8 kg and the maximal force in the surge and sway and yaw moment are [10; 10; 10], respectively. These scaled numbers represent the full-scale ship weights 8163400kg and forces/ moment constraint to [3430000; 3430000; 240100000], respectively. The scaled-up law follows Froude scaling law (Moreira, Fossen, & Guedes Soares, 2007).

The other parameters of this model ship are presented in literature (Skjetne, Smogeli, & Fossen, 2004). The settings of PD controllers are: Kd= diag([200,200,10]); Kp = diag([5,5,5]); The target-ship is assumed to keep its motion. The layout of this scenario is presented in Table 3.

Table 3 Settings of scenario

	Position [NM]	Heading [deg]	Speed [knot]	DCPA [NM]	TCPA [h]
Own Ship	(0,0)	000	10.0	-	-
TS1	(4.24,4.24)	248	18.4	0	0.25

Following the methods presented in Section 2, we generate VO set and UO set of the TS1 and present in Fig. 6 (2) and (3). In Fig. 6 (2), we ignore the dynamic model of the OS and assume the OS can change its velocity immediately. In return, we calculate the I-ICRA = 0.38, which means the ship has more than half chance to avoid a collision and the encounter scenario, which is not such urgent. However, if we consider the ship's dynamics and constraints (e.g. the maximal forces and moment), the I-ICRA rises to 0.63. That is because most of the collision-free solutions in Fig. 6 (2) are not reachable given constraints and the PD controller. In the UO set, the shadow area represents the velocity is reachable for the OS but leading to collision; the white region is the reachable and collision-free solution to the ship.

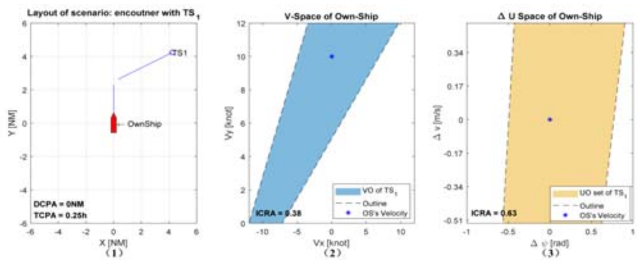


Figure 6. The encounter scenario when we consider the manoeuvrability of the OS.

4 DISCUSSION

4.1 *Comparing between ICRA and other CRI methods (based on CPA)*

Three difference between CRI methods and ICRA are identified in this paper. Firstly, ICRA defines the collision risk as the chance of avoiding a collision which considers the ability of the OS to avoid a collision, while most of CRI methods ignore this part. Secondly, ICRA maps all the obstacles into resolution space (i.e., V-space) together and then measures the collision risk, whereas the CRI methods decouple the traffic first and then assess the risk in each pair of ships. Thirdly, the construction of ICRA is relatively independent of the experts' judgment.

4.1.1 *ICRA considers the ability of the OS to avoid a collision*

Fig. 7 shows the bow-tie model of the OS encounters with three target-ships (TS1, TS2, and TS3). The collision between TS1 and the OS means the path (say Path 1) between TS1 and the top event (or "Collision") is connected.

The CRIs indicate the connectivity of these paths. If one TS's risk index exceeds the threshold, the path between this TS and the OS is connected, which implies this TS is dangerous for the OS. Then, a collision alert is triggered. However, this approach ignores the "barriers" on the path which can block these paths from TSs to the top event. Here, the barriers can be interpreted as maneuvers. Before collisions happen, the OS is capable to take all kinds of maneuvers to block the paths, i.e. avoid the collision. In Section 3.2, we show that even the upcoming ship (e.g. TS3) has the same CRI, the room-for-maneuver of the OS to avoid collision is different. In the first scenario, the OS can take either port turns or starboard turns to avoid the collision, while in the last scenario, the OS can avoid the collision if and only if the ship chooses a hard port-turn. Thus, the last scenario should be more dangerous than in the first scenario. The CRI methods only consider the dangers level of "threats" (the approaching ships) but ignore the chance of the OS to avoid the "threats". Therefore, CRI methods cannot distinguish the difficulty of the OS tackling these threats.

ICRA is designed to consider the ability of the OS's maneuverability to prevent a collision. In returns, ICRA not only measures the danger levels of the threats (TSs) but also present the ability of the OS blocks the paths. When the ICRA exceeds the thresholds, it basically tells the officer on board that the coming threats (TSs) are not only dangerous but also difficult to find a solution to prevent collisions.

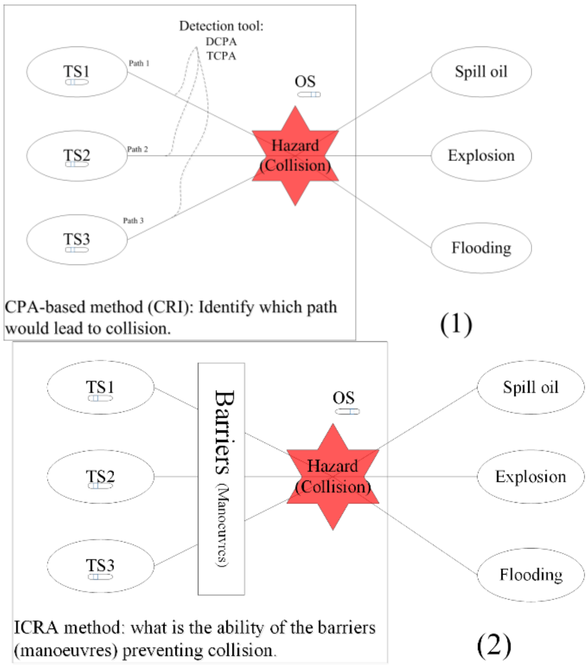


Figure 7. Bow-tie model of the ship collision event.

4.1.2 *ICRA measures the collision risk of traffic as a whole*

The ICRA measures the collision risk as a whole, which can prevent two drawbacks of CRI methods in multiple-ship cases.

The decoupling technique loses some information about the traffic, which results in biases in collision risk assessment. As Section 3.2 shown, a well-organized scenario is less dangerous than the traffic in chaos, even the risk index of each pair in these scenarios remains the same. The CRI cannot show these differences to the OOW, but the ICRA could.

Inconvenience in finding conflict resolutions. CRI only shows the risk in pairs and ignore the impacts of other ships. Thus, when we find one solution reducing the risk in one pair of ships, we cannot guarantee this solution can also reduce the risk in another pair. In some worse cases, this solution might create some new conflicts. Thus, the OOWs need to try and test the solutions in each pair of ships, until they can find the one which reduces all the conflict in each pair of ships. Conversely, the ICRA measures the collision risk as a whole and it can directly identify collision-free solutions to the OOWs. The target-ship who is temporarily not in conflict is also considered in the ICRA. As a result, the solutions identified by the ICRA method can solve all the conflicts and would not create a new conflict.

4.1.3 *Independent from the experts' judgment*

The setting and meaning of ICRA are independent of the OOW and experts, while the construction of CRI methods strongly relies on expert's knowledge. Moreover, there is a lack of general agreements on the settings of CRI (Goerlandt et al., 2015). That means the same scenario might have different CRIs and different conclusions when the different experts are involved. On the other hand, the construction of the VO set relies on the obtained traffic data and the RV set depends on the maneuverability of the ship, which is relatively independent of experts. Additionally, the meaning of ICRA is also clear. When the value of ICRA reaches 1, then the OS is inevitable collide with obstacles, even the collision has not happened yet. When ICRA is 0.5, that means if the OS chooses the solutions randomly, the ship still has 50% to collide with other ships.

4.2 *Potential applications*

The ICRA offers a new perspective to measure collision risk, which can rich the tools for risk-informed decision making on board. In literature (Goerlandt et al., 2015), researchers proposed a framework for risk-informed collision alert, which helps share situational awareness between experts and OOWs. Some widely used indicators are listed, but few indicators reflect the ability of the ship to avoid a collision and consider the entire traffic. ICRA can be used as one indicator in this framework which offers some information about the difficulty of the OS ship avoiding collision with the entire traffic.

ICRA also can be used in risk-based decision making, e.g. collision avoidance. ICRA consists of VO set and RV set which can help the OOWs to eliminate the solutions leading to collisions and find the collision-free solutions to all the encountering ships.

5 CONCLUSION

In this paper, Immediate Collision Risk Assessment (ICRA) is proposed to measure collision risk in a dense traffic environment, i.e. multiple-ship scenarios. The collision risk is measured by the percentage of the maneuvers (velocities) leading to a collision. To tackle the dynamics of ship and constraints on forces, an improved-ICRA is proposed, where the generalized velocity obstacle (GVO) algorithm is applied.

Three groups of scenarios have presented. The first group of scenarios shows the performance of ICRA when the number of Target Ship (TS) is increasing; the second group of scenarios shows the proposed ICRA is enabled to measure the collision risk in different traffic modes, specifically well-organized traffic case and chaotic traffic case. These two cases show ICRA is suitable to use in multiple-ship scenarios. The last scenario demonstrates the improved-ICRA that considers ship dynamics and force constraints. It shows that the collision risk is underestimated when we ignore the ship dynamics and constraints on forces.

Three features of ICRA have been identified in this paper: (1) it measures the collision risk considering the ability of the Own Ship (OS) to avoid dangers; (2) it measures collision risk of the entire traffic instead of decoupling the traffic, which is more suitable in multiple-ship scenarios; (3) the measurement is independent from experts' opinions. We believe that the proposed ICRA offers a new perspective in collision risk measurement, which not only enriches the choices in the developments of risk-informed collision alert systems but also can support the risk-based collision avoidance in multiple-ship scenarios.

Future research will consider the following directions. Firstly, the influence of regulations, e.g. COLREGs, will be included. If the OS complies with regulations, the size of RV set will be modified and then the measured risk is changed, e.g. (Y. Huang & van Gelder, 2019). Secondly, the environmental disturbance would be considered to support collision avoidance in different environmental conditions. Thirdly, the potentials of using ICRA on board ship and in vessel traffic service center in various scenarios need more studies.

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