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An improved time discretized non-linear velocity obstacle method for multi-ship encounter detection

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ABSTRACT

Ship collision is one of the major contributors of maritime accidents. Quantitative risk analysis of such accidents is an effective tool for maritime safety administrations to understand the current risk level and propose risk mitigation measures. In this paper, an improved Time Discretized Non-linear Velocity obstacle (TD-NLVO) algorithm is proposed to detect multiple ship encounter situations using historical AIS data. Boolean operation on the individual NLVO is integrated with TD-NLVO using the union of the velocity-obstacle sets to determine a dangerous encounter situation according to the pre-set criteria. Two case studies are implemented to illustrate the capability of the proposed algorithm. A comparison is conducted between the previous and the improved methods. The results indicate that the improved method can effectively identify a multiple ship encounter which satisfies the pre-set criteria. The improved method has the potential to provide more detailed information for stakeholders e.g. maritime safety administration, etc. to propose risk mitigation measures as well as to improve the accuracy of geometric probability analysis for ship collision risk.

1. Introduction

Currently, the world economy is closely connected to the maritime transport system, with its advantages in large volume of transportation and low cost, etc. However, ship collision, as one of the major contributors to maritime accidents, poses an unneglectable risk to the societies and environment, in terms of its consequences of loss of human life, property and environmental pollution (EMSA, 2017; Goerlandt and Montewka, 2014; Goerlandt and Montewka, 2015). The occurrence of ship collision accident and its consequences may also induce unexpected impacts on the various stakeholders that participate in the complex network, e.g. port authorities, maritime safety administrations, etc. (Chen et al., 2019b). It is therefore important to conduct research on risk analysis and management of such accidents in order to reduce their occurrence and provide a safer environment for maritime traffic.

Quantitative Risk Analysis (QRA) is one of the most popular risk analysis and management methodologies in the maritime industry, as it can provide a quantified measurement of risk and its consequences, and thus facilitate decision-makers to propose risk mitigation measures, e.g. (Baksh et al., 2018; Goerlandt and Montewka, 2015; Pedersen, 1995). In maritime traffic discipline, the framework proposed by Fujii (Fujii and Shiobara, 1971) and Macduff (1974) has gained much attention from both the academia and industry, which is shown in Eq. (1):

$$P_{Collision} = P_{Geometric} \times P_{Causation} \tag{1}$$

Where probability of ship collision is estimated from two aspects: 1) Geometric probability, also known as the number of collision candidate, which is the description of the probability of ship encounters that have the potential for collision; and 2) Causation probability which is the description of the probability of the dangerous ship encounters that finally results in accident due to various factors, e.g. human and mechanical failures, extreme weather conditions, etc. The two elements jointly estimate the probability of ship collision accident from the aspects of dangerous encounters and the failure of collision avoidance due to multiple contributing factors, respectively.

Under this framework, obtaining the geometric probability is the first step for collision risk analysis. Identification of the ship encounters that have potential of collision based on their spatial-temporal proximity

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is the critical process for the estimation of geometric probability. Due to the scarce occurrence of collision accidents, however, it is challenging to conduct research by totally relying on historical accident records. Under this situation, the dangerous encounters - often defined as collision candidates, or near misses - i.e. the encounters that have the potential of a collision, have become one of the key research interests in the field. Therefore, the work in this research is of potential significance in geometric probability estimation.

To detect this type of ship encounters from historical traffic data, various researches have been conducted. In general, these works fall within three major categories: 1) synthetic indicator approach; 2) safety boundary approach; and 3) velocity-based approach, respectively, according to the criteria utilized in the research to determine the encounter. Interested readers can refer to the literature review work by the authors (Chen et al., 2019b) for detailed information. Spatial and temporal proximities are the critical elements these approaches measure. For synthetic indicator approaches, CPA values (DCPA, TCPA), relative speed, course, relative distance, etc. are used to measure spatial-temporal proximity directly, or construct mathematical models based on these indices. (Debnath and Chin, 2016; Zhang et al., 2017; Zhen et al., 2017). On the other hand, the safety boundary approach utilizes a pre-set boundary in space to determine if the spatial-temporal relationship between ships violate the pre-set criteria (Chai et al., 2017; Montewka et al., 2010; Szlapczynski and Szlapczynska, 2016). In both these approaches, the spatial and temporal proximities between ships are often considered separately or combined as certain numerical values as indices to determine the collision candidate. One of the critics for these approaches would be the difficulty to determine and express a physical meaning of such values. In this context, the velocity-based approach aims to unify spatiotemporal proximity, and transform the spatial-temporal relationship between own ship and target ship into the velocity domain; this is introduced to determine the criterion of collision risk and to measure the risk, e.g. (Chen et al., 2018b; Huang and van Gelder, 2019; Huang et al., 2018; Lenart, 1983; Lenart, 2015), etc.

The detection of a collision candidate or near-miss situation has been well developed with the aforementioned works. However, there are still some issues which compromised the accuracy and reliability of the results: 1) the potential of under/overestimation of collision candidate due to the analysis method that only considered the data at certain time intervals; 2) no consideration of multi-ship encounter situations during collision candidate/near miss detection. For the traditional methods, the collision candidate is usually identified via pairwise analysis, which in practice, however, is not always realistic as for areas where maritime traffic is heavy and congested, the encounters could be complicated in the sense that multiple ships may participate. For aforementioned situations, the pairwise analysis may have influence on the accuracy and reliability of the results. Secondly, the causation risk probability risk for two-ship encounter and multi-ship encounter may be different in regard to their encounter complexity.(Chen et al., 2019c; van Westrenen and Ellerbroek, 2017; Wen et al., 2015), as in some accident the own ship intended to avoid collision with one ship (TS1) but collided with the another ship (TS2). Without the influence of TS1, the ship might not collide with TS2, vice versa. To further facilitate the development of a method for estimating the geometric probability of ship collision for multiple ship encounter situations, the key research problem in this paper is to design a method that can detect multiple ship encounters that satisfy the pre-set criteria of collision candidate. Although recently new researches have been conducted with useful insights on identifying collision candidate/near miss in an area, the above research problem remains to be addressed. For instance (Fang et al., 2019), improved the parameter robustness of the model proposed by Zhang et al. (2017) and conducted a risk analysis of collision candidate in Xiamen port. Zhao et al. (2019) conducted agent-based modelling to analyse the encounter rate in the region, which is similar to work done by Goerlandt and Kujala (2011). All these works rely on the existing methods for collision candidate detection in pairwise encounters, which lack consideration of the multi-encounter situation. This paper presents one step forward to identify and analyse the multi-ship encounters from historical AIS data, to further facilitate collision risk analysis in the waterways.

In previous work by the authors (Chen et al., 2018b), a novel collision candidate detection method following velocity-based approach is proposed, named as Time Discretized Non-linear Velocity Obstacle (TD-NLVO), where the encounter is considered as a process instead of a set of time slices, allowing to reduce the possible under/overestimation of the results. As the successor work, this research aims to propose an improved ship collision/near miss detection method which can identify multiple encounter situations from the historical Automatic Identification System (AIS) data based on an improved TD-NLVO (I-TD-NLVO). To do this, the combination of multiple Velocity Obstacle (VO) sets induced by different target ships is introduced.

The contents of this paper are as follows: Section 2 illustrates the framework of the method proposed. This is followed by a detailed introduction to the components of the methods in Section 3. A detailed introduction to the design of the algorithm is shown in Section 4. Section 5 is the case study to verify the efficacy of the improved method and determine whether it can identify the dangerous encounters and differentiate between single encounter and multiple encounters. In section 6 a comparison between the improved algorithm and previous work is conducted, followed by a detailed discussion on the combination of individual velocity obstacles. The conclusions of this research are presented in Section 7.

2. The framework of the method

When a ship navigates in the waterway, she may encounter many target ships and get involved in a complicated encounter situation where the velocity of own ship has the violation of individual VO sets of multiple targets at the same time. Such an encounter scenario is termed as multiple ship encounter in this paper.

Fig. 1 gives the frameworks of the core algorithms in previous TD-NLVO and the improved method, respectively. In the previous work by the authors (Chen et al., 2018b), the detection of collision candidate was conducted by analyzing each pair of ships in the predefined area. If a violation of the non-linear velocity obstacle induced by the target ship is detected, the pair of ships will be considered as a collision candidate (Fig. 1 (a)). However, during this process, situations, where the own ship could encounter with many target ships, was decomposed into many two-ships sub-situations, which could result in potential overestimation of the number of collision candidate. Moreover, for the situation where more than 3 ships are involved, the computational burden will be increased due to this decomposition.

Besides, compared with the ordinary situation where only two ships are involved, multiple ship encounter situation would be difficult for the decision-making process of the collision avoidance of the own ship since no clear rules or regulations are adopted for such a scenario. Therefore, it should not be considered equivalent to the simple encounter situation where only two ships are involved when modelling the risk for these situations.

To fulfil the goal of identifying multiple-ship encounter, in this paper, a two-step encounter situation analysis process is proposed: firstly, the NLVO induced by each target ship at each time spot of the own ship's trajectory is obtained with the same algorithm in the previous work. Secondly, the individual velocity obstacles induced by target ships are integrated as a combined NLVO using the Boolean operations of the polygon (e.g. "union"). A violation detection on the combined NLVO is then conducted. If there is a violation of the combined NLVO, a detailed violation analysis is conducted to identify which target ships are the contributors to the situation. With this operation, the multi-ship encounter which satisfies the pre-set criterion of collision candidate can be detected from the historical AIS data.

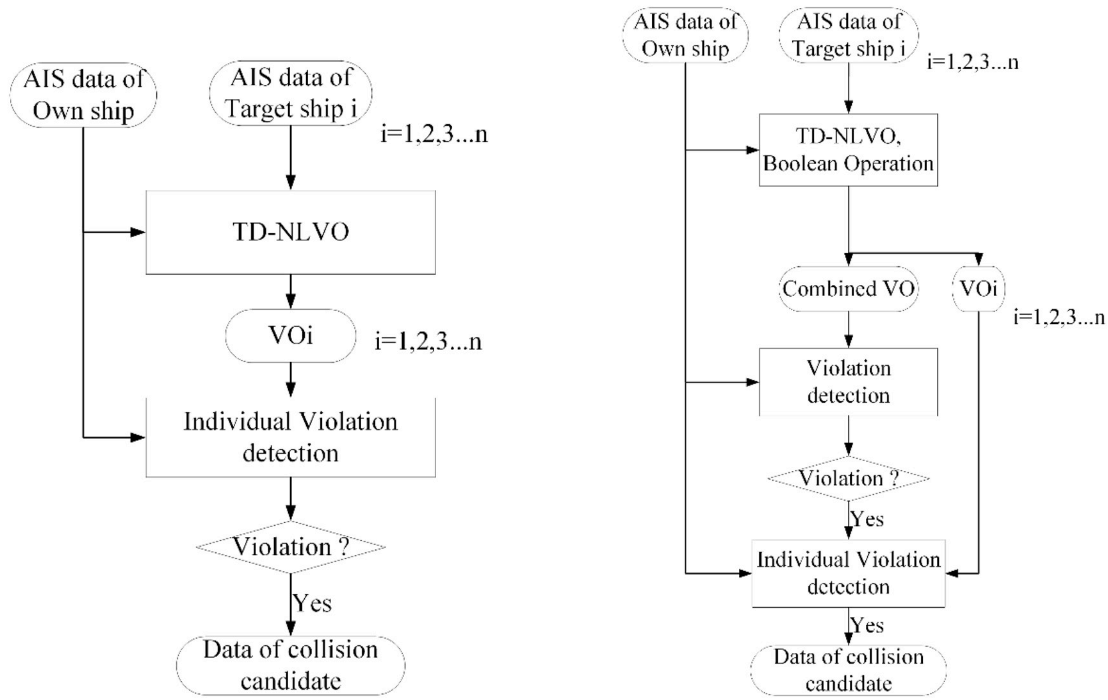


Fig. 1. Framework of the core algorithm in previous work and the improved algorithm
(a) Core algorithm in (Chen et al., 2018b) (b) Core algorithm in the improved algorithm.

3. Collision candidate detection methods

To identify the dangerous encounters that have the potential for collision, the indices or models that can reflect the spatial-temporal proximity between ships have been widely introduced as the instruments, e.g. CPA and its values, etc. However, when in the application, the spatial-temporal proximity is often considered separately or combined as a numeric indicator which lacks physical meaning. In certain situations, e.g. when DCPA and TCPA offer contradictory results, it would be difficult to determine the risk level of encounter situation. Velocity, meanwhile, is an indicator that can unify the spatial and temporal proximity in one dimension. Therefore, in this research, we utilized the velocity obstacle-based approach to detect the encounters that can be considered as collision candidates.

3.1. Time-discrete non-linear velocity obstacle algorithm

VO algorithm is an effective and intuitive method for collision avoidance in many disciplines, e.g. motion planning e.g. (Fiorini and Shiller, 1998), autonomous ships, e.g. (Zhao et al., 2016), navigational assistant for the OOWs, e.g. (Huang et al., 2019b), etc. It describes sets of velocities where, if the velocity of the chosen object (e.g. own ship in maritime domain) falls into a set, a certain spatiotemporal proximity situation will happen in the future of the detection time, i.e. the dangerous encounter can be identified with the indicator of velocity, with its inherent nature that can express such spatial-temporal proximity simultaneously. This set is also called a VO set.

In (Chen et al., 2018b), the authors proposed a TD-NLVO algorithm to detect collision candidate using historical AIS data. As mentioned in Section 1, the collision candidate, in this case, is identified from the perspective of a process rather than of certain time instances, and velocity obstacle set is introduced as the criterion to determine the collision candidate. The basic principle of TD-NLVO is shown in Fig. 2.

Suppose that ship A and B are in an encounter situation (Fig. 2 a) and their kinematic information (e.g. position, velocity, heading, etc.) are known. The state of ship A and B is expressed as $A\{L_A,\ P_A(\mathrm{t}),\ V_A(\mathrm{t})\}$and $B\{L_B,\ P_B(t),\ V_B(t)\}$, respectively, where L, $P(\mathrm{t})$, $V(\mathrm{t})$ are the length, position, and velocity of each ship at time t. The spatial relationships between the two ships can be transformed into the velocity domain of the own ship (Ship A), which is shown in Fig. 2b. The circular area in Fig. 2 denotes an area around the own ship where ship B could possibly be when the collision happens, which is defined as ConfP (Huang et al., 2018) and can be obtained according to Eq. (1):

$$ConfP = \{\|P_A(t) - P_B(t)\| \le R\} \tag{2}$$

where P denotes the position of ships at time t and $\|\cdot\|$is the Euclidean distance between them. R is the pre-set safety distance threshold. From the perspective of the own ship, Eq. (1) can be rewritten into Eq. (2):

$$P_A(t_C) \in P_B(t_C) \oplus ConfP \tag{3}$$

where $P(t_C)$is the position of ship A and B when the collision happens and $\oplus$is the Minkowski addition. Considering the assumption that kinematic information of both ships is known, Eq. (2) can be substituted with Eq. (3):

$$\mathrm{VO}_{\mathrm{A|B}} = \bigcup_{t}^{\infty}\left(\frac{P_{\mathrm{B}}(t) - P_{\mathrm{A}}(t_0)}{(t - t_0)}\right) \oplus \frac{ConfP}{(t - t_0)} \tag{4}$$

where $\mathrm{VO}_{\mathrm{A|B}}$denotes the Velocity sets of the own ship induced by ship B and $t_0$is the time of detection. This equation is considered as the criterion of collision candidate/near miss identification, i.e. if the velocity of the own ship satisfies Eq. (3), the pre-set spatial relationship between own ship and target ship will be satisfied if the own ship maintains her velocity.

3.2. Determination of multiple ship encounter situation

For ships navigating in water areas with heavy maritime traffic, e.g. busy ports and important waterways, the encounter situations are complicated when multiple ships (more than 2) are involved. Due to the fact that the International Regulations for Preventing Collisions at Sea (COLREGs) only provides rules and guidance for collision avoidance between two ships, such situations require the Officers on Watch (OOWs) to evaluate and prioritize the risk of collision caused by each

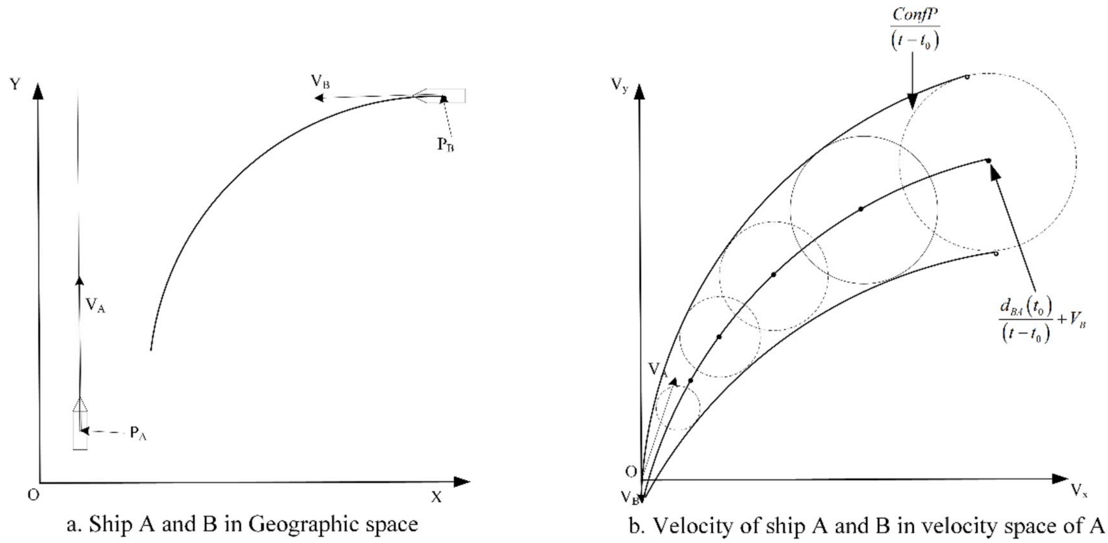


Fig. 2. Demonstration of non-linear velocity obstacle (Chen et al., 2018b).

individual encounter, and propose and execute a global avoidance manoeuvre to safely pass the target ships. During this process, the decision-making process and their room to manoeuvre is also constrained by the influence of multiple target ships, which increases the risk of collision in such situation, compared with the simple encounter where only 2 ships are involved.

To better grasp the picture of the collision risk in certain regions, it is necessary to analyse the collision candidate/near-miss with more detail. A multiple encounter situation detection procedure is proposed based on the Boolean operation "Union" on the polygons. A simple illustration is shown in Fig. 3.

Suppose that ship A, B, and C are in an encounter situation shown in Fig. 3a, and their kinematic information is known. Based on the traditional TD-NLVO, such situation will be decomposed into two situations and be analysed separately, which will result in a redundant record in the collision candidate list. To solve this problem, here the Boolean operation on polygons is introduced. The velocity obstacles of ship A induced by B and C can be merged as one as indicated by Fig. 3b, which allows ship A to evaluate if her velocity has violated the combined NLVO. The individual NLVO induced by each target ship will be utilized to determine which target ship has contributed to such violation. The Boolean operation on polygons is a popular technique in computational graphics and geosciences. A complicated shape can be generated with multiple polygons using the Boolean operation such as "union" (combine), "intersect", etc. (Martínez et al., 2009). In this research, such a technique is introduced to perform the combination of NLVO sets with open software libraries such as "PolyBoolCS[1]" "polybooljs[2]". To do this, each VO induced by the data point of a target ship is first discretized as a polygon shape of 20 points, then the "union" operation is performed to combine the separated VOs as a large area, which represents the individual NLVO induced by a target ship. On the basis of the individual NLVOs, one or multiple combined NLVO will be obtained to represent the multiple encounter situation in the velocity domain of the own ship.

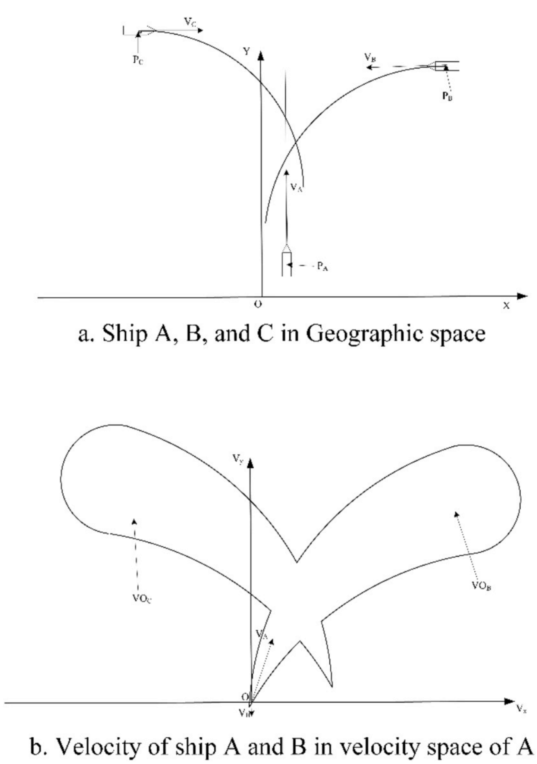


Fig. 3. Illustration of multiple encounter situation and Boolean operation on polygons.

4. Implementation of the improved TD-NLVO

As one of the critical elements in probabilistic risk analysis of ship collision accident, identification of collision candidate/near miss is the first step to quantify the risk and its characteristics. For that purpose, the TD-NLVO and Boolean operation on polygons are integrated into this research. A modified criterion of collision candidate as shown in Eq. (4) is introduced as the basis of the algorithm:

$$
\begin{aligned}
\mathrm{VO_A} &= \bigcup_{j=1}^{n} \mathrm{VO}_{\mathrm{A}\left|\mathrm{Ship}_{j t_i}\right.} \\
\mathrm{VO}_{\mathrm{A}\left|\mathrm{Ship}_{j t_i}\right.} &= \left(\frac{P_{Ship_j}(t_i) - P_A(t_0)}{(t_i - t_0)}\right) \oplus \frac{ConfP_{Ship_j}}{(t_i - t_0)}
\end{aligned}
\tag{5}
$$

where $\mathrm{VO_A}$ is the non-linear velocity obstacle sets of the own ship (ship A) induced by the other ships in the encounter situation, which is the union of all non-linear velocity obstacle sets induced by each target individually, t_0 is the time of detection, and t_i is the future time step. Each

[1] https://github.com/StagPoint/PolyBoolCS.
[2] https://github.com/voidqk/polybooljs.

non-linear velocity obstacle set induced by one target ship ($Ship_j$) is obtained following the criterion in the previous work, with the circular shape of ConfP. In principle, one can also use other shapes of criteria for collision candidate detection, e.g. elliptical ship domain, etc. However, since the goal of this paper is to propose the method that can detect multiple ship encounter, the basic shape of the criteria is considered here. It is also plausible to apply other complicated shapes of the criteria, e.g. elliptical ship domain, etc. into the algorithm, considering the local ship traffic characteristics when in practices. To make a comparison with the previous work, the parameter of the ConfP is indicatively set to be 500 m in the proposed method and previous TD-NLVO. Based on the criteria of Eq. (4), an improved TD-NLVO for the multi-ship encounter is proposed as Algorithm 1 illustrates (for a three ships encounter scenario):

Algorithm 1. Ship domain-based Time-discrete Non-Linear Velocity Obstacle for multi-ship encounter detection

```
Input: AIS data of ship A (own ship) and target ship 1,2, … n;
  for P_i in trajectory A
    for every target ship j
      for P_m in AIS data of target ship j where P_m.time ≥ P_i.time
        Radius of ConfP=500 m;
          Calculate the distance between own ship and target ship j;
          Calculate the centres of ConfP of target ship j;
          List<ConfP> NLVO_ship_j.Add (ConfP);
        end for;
        individual_NLVO_ship_j=Boolean operation (NLVO_ship_j);
        List<Polygon> individual_NLVO.Add(individual_NLVO_ship_j);
        List<MMSI> name_of_target_ship.Add(name_of ship_j);
    end for;
    Combined_NLVO_i=Boolean operation(individual_NLVO);
    Store the data of individual VOs and corresponding ship names;
    List<polygon> combined_VO.Add (Combined_NLVO_i);
  end for;

  if (combined_NLVO ≠ [])
   for each Combined_NLVO_i
    determine if the velocity of own ship at each moment violate the combined NLVO;
      if (violation==true)
        store the time and name of own ship and the shape of the combined NLVO;
        determine which individual ship contribute to the violation;
        store the contributor and its individual NLVO;
      end if;
   end for;
  end if;

  if (violation of combined NLVO ≠ [])
  Output_1: Record of violation of combined NLVO at each data point of own ship A (time, true or
false of the violation, true or false of the multiple-violation, the shape of the combined NLVO);
  Output_2: Record of violation of individual NLVO at each data point of own ship A (name of the
contributor, shape of the corresponding individual NLVO);
  end if;
```

The principle of the algorithm is as follows: Suppose that ship A, and multiple ships are in an encounter situation. Ship A is selected as the own ship. For each data point $P_i$of ship A's trajectory, set $P_i.time$as the detection time for this point. All the AIS data of the target ships whose time is later than $P_i.time$are collected and are transformed into NLVOs induced by them according to Eq. (4). For each target ship j, each discrete ConfP induced by the data point in the AIS data will be obtained using Eq. (4), and all the ConfP are combined as one individual NLVO using Boolean operation on polygons to represent the NLVO induced by the target ship j at $P_i.time$. During the process, the ConfP are firstly discretized as polygons with 20 points and then developed with the Boolean operation. When all the individual NLVO induced by target ships are obtained, the combined NLVO which represents the multiple encounter situation at $P_i.time$ is obtained with the help of the union operation. The velocity of own ship will be analysed to determine if there is a violation of the combined NLVO. If so, the time and the ship name which caused the NLVO violation will be recorded for further analysis. The individual NLVO violation detection will be further performed to decompose the multi-ship encounters into pairwise analysis between the own ship and each of the target ship, to verify if there are multiple violations with target ships and determine the contributor to the encounter situation. With such design, the encounters with the participation of multiple ships (more than 2) can be identified from the historical AIS data to facilitate the estimation of the geometric collision probability in the waterways with more insights on the characteristics of ship encounters. In the meantime, the analysis of the multi-ship encounter could also be beneficial for the collision avoidance of the individual ships. However, due to the scope of this research, interested readers on such a topic please be referred to (Huang et al., 2019b) for details.

5. Case study

In this section, two case studies were performed to verify the capability of the proposed method for detecting multi-ship encounter process. Case 1 is an encounter situation where four ships are involved, and the own ship has a multiple encounter situation with two of the target ships. Case 2 is a more complicated encounter situation where multiple ships are involved and the own ship has VO violation processes with multiple target ships at the same time.

To do this, historical AIS data from the open-access of the Danish Maritime Authority was utilized as the test datasets. The velocity information (speed and course) in this research utilizes the speed over ground and course over ground to represent the movements of ship in regards to the true ground coordinate system, and to represent the scenario detecting the traffic situation form a third-party (e.g. MSA) view based on the observation of the data. However, to utilize the Velocity-based approach for individual collision avoidance on board, the speed over water and heading should be used. The objective of these case studies is to verify the effectiveness of the proposed algorithm. Here we utilized two different sets of data for 15 min each as test data sets. The description of the data sets is shown in Table 1. To keep the name of the ships anonymous, the middle three digits of the MMSIs (Maritime Mobile Service Identifier, MMSI) is replaced with "XXX".

Table 1
Description of the test data.

No.	Duration of Data	Own ship	Ships involved
1	4-10-2018 9:45 to 10:00	219XXX172	219XXX307, 219XXX172, 304XXX000, 578XXX100
2	26-10-2018 4:45 to 5:00	219XXX000	219XXX543, 219XXX416, 219XXX477, 219XXX903, 219XXX000, 219XXX000, 231XXX000, 304XXX688, 304XXX000,

5.1. Encounter scenario 1

In this case, 15 min of AIS data are utilized to test the proposed method, where “219XXX307, 219XXX172, 304XXX000,578XXX100” are the ships involved in the duration. “219XXX172” was chosen as the research object (Own ship). To apply the proposed algorithm, the radius of the safety region is set as 500 m. Based on the results of the method, a multi-ship encounter between the own ship “219XXX172” and target ships “578XXX100” and “304XXX000” was detected. Table 2 and Fig. 4 illustrate the results of encounter detection and a snapshot of positions of ships, combined NLVO of own ship induced by target ships, and Violated NLVO of the target ship:

From Table 2 one can see that the own ship has the violation of the combined non-linear velocity obstacle sets and individual violations with both two target ships within the detection time span, respectively. The duration of detected NLVO violation for the two ships is different and they share an overlap in time, which means that during the encounter process there was a period of time the own ship has violated the individual NLVOs at the same time. These findings can be confirmed in Fig. 4. In Fig. 4, the positions of ships at each time step, and the combined NLVO of target ships are shown in the column a and b, respectively. The decomposed NLVO to represent the violation of NLVO induced by each target ship are shown in column c. It is clear that the combined NLVO of target ships is composed of multiple individual NLVOs of each target ship. From Fig. 5 (1, b) and (1, c) one can see that the violated NLVO induced by ship “578XXX100” is smaller than combined NLVO, and the results indicate that own ship only has violation with “578XXX100”. This indicates that the NLVO of other targets is “combined” into the large NLVO during the Boolean operation “Union” and the velocity of own ship does not have violation with them. As for Fig. 4(2, b) and (2, c), one can see clearly the combined NLVO is made by two different individual NLVOs showed in (2, c) and the own ship has the violation of each individual NLVOs. As for Fig. 4(3, b) and (3, c), one can see that the velocity space of the own ship is filled by the NLVO. This indicates that the current spatial-temporal proximity already satisfied the pre-set criteria. With this design of algorithm, the collision candidate detection process can be processed in this manner: firstly, determine if there is a violation of combined NLVO at each step, if there is a violation, then determine which individual ship caused such violation with the own ship. In this way, a detailed analysis of the encounter process can be conducted.

5.2. Encounter scenario 2

In the previous section, a case scenario where the own ship has velocity violation of the non-linear velocity obstacle sets induced by two target ships is illustrated. Here a more complicated situation where multiple ships are involved in the encounter scenario is utilized to illustrate the capability of the proposed algorithm to detect multi-ship encounter process. The results of collision detection and a snapshot of positions of ships, combined NLVO, and violated individual NLVO or target ships are shown in Table 3 and Fig. 5 respectively:

During the detection period, 9 ships participate in navigation in the water area. The own ship has violated the individual NLVOs of three target ships successively, as Table 3 indicates. One can see that during the process, there are overlaps of time for the individual NLVOs violation period, which indicates that during such an encounter process, the velocity of the own ship has violated the NLVO induced by the multiple target ships simultaneously. The combined NLVO induced by the multiple target ships is decomposed and shown in the sub-figures in column c of Fig. 5. For example, during 04:45:07 to 04:50:33 the own ship and target ships “219XXX903, 231XXX000, 304 XXX 000” formulated a four-ship encounter that satisfied the criterion of collision candidate during the encounter process. This can also be proved in Fig. 5. From Fig. 5 (1, b) and (1, c), one can see at time step “04:46:27” the velocity of own ship violated the combined NLVO and especially, violated the NLVO induced by the ships “219XXX903, 231XXX000, 304 XXX 000” (Fig. 5 (1, c)). While at time step “04:53:46” one can see the velocity of own ship violated the VOs of the ship “231XXX000”, “304 XXX 000” simultaneously (Fig. 5 (2, c)). At time step “04:58:18” the own ship only had velocity violation with target ship “304 XXX 000”. Based on the results, one can see that the proposed method has successfully detected the multiple encounter situation during the encounter process. The detailed record of such an encounter can be utilized for further analysis of the characteristics of each phase of the encounter (e.g. single encounter-multiple encounter-single encounter, etc.). The evolution of the encounter process in the velocity domain of own ship can be found in Gif. 1.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.oceaneng.2019.106718.

Table 2
Description of VO violations.

No.	MMSI of VO violation	Detection period	Description
1	219XXX172, 304XXX000	09:46:23 to 09:48:57	Individual violation
2	219XXX172, 578XXX100	09:45:35 to 09:52:50	Individual violation
3	219XXX172, 304XXX000, 578XXX100	09:46:23 to 09:48:57	Multiple violation
4	219XXX172, 578XXX100	09:46:23 to 09:52:50	Individual violation

5.3. Multi-ship encounter detection

To further verify the proposed method, another data set which are AIS data from 09:00 to 21:00 on Oct. 15th are utilized to identify the multi-ship encounter situations in the area of the case study. The original TD-NLVO are also introduced to make the comparison. The detailed information and their corresponding data obtained from TD-NLVO are also shown in Tables 4 and 5, respectively.

As Table 4 indicates, in total 6 cases of multi-ship encounter situations are identified from the AIS data, the start and end of the detection time are also included. According to the results and the aforementioned two cases of detailed illustration, one can see that the proposed improved TD-NLVO can identify the encounter situation where multiple ships are involved. Besides, as Table 5 shows, for each case of a multi-ship encounter, the previous method has separately determined if the encounter between two ships violate the pre-set threshold. To obtain the information of possible multi-ship encounter, additional work has to be done to search for which ships have encounter with multiple targets. Although such work could be conducted by searching in the results in Table 5, there is a fundamental difference between the two methods: Within the design of the original TD-NLVO, the multi-ship encounter situation is decomposed into pairwise analysis, as the other existing models for collision candidate detection do to simplify the detection process. However, the potential influence of other targets on the two encountered ships, which can be represented in the form of a united velocity obstacle in the velocity domain of the own ship, is also ignored as the method treats the encounters independently and equally. The difference may not be significant on obtaining the number of collision candidate, however, as the framework shows in Eq. (1), the probability of collision also considers the causation factors, which can be influenced by the complexity level of the encounter situation as shown in (Chen et al., 2019c). By considering the multi-ship encounter situation and identifying them with historical AIS data, the information can be integrated into the causation risk modelling of collision. From this perspective, we think the consideration of multi-ship encounter within the design of the method is an improvement for probabilistic risk modelling of ship collision.

6. Discussions

In this section, a comparison between the improved algorithm and

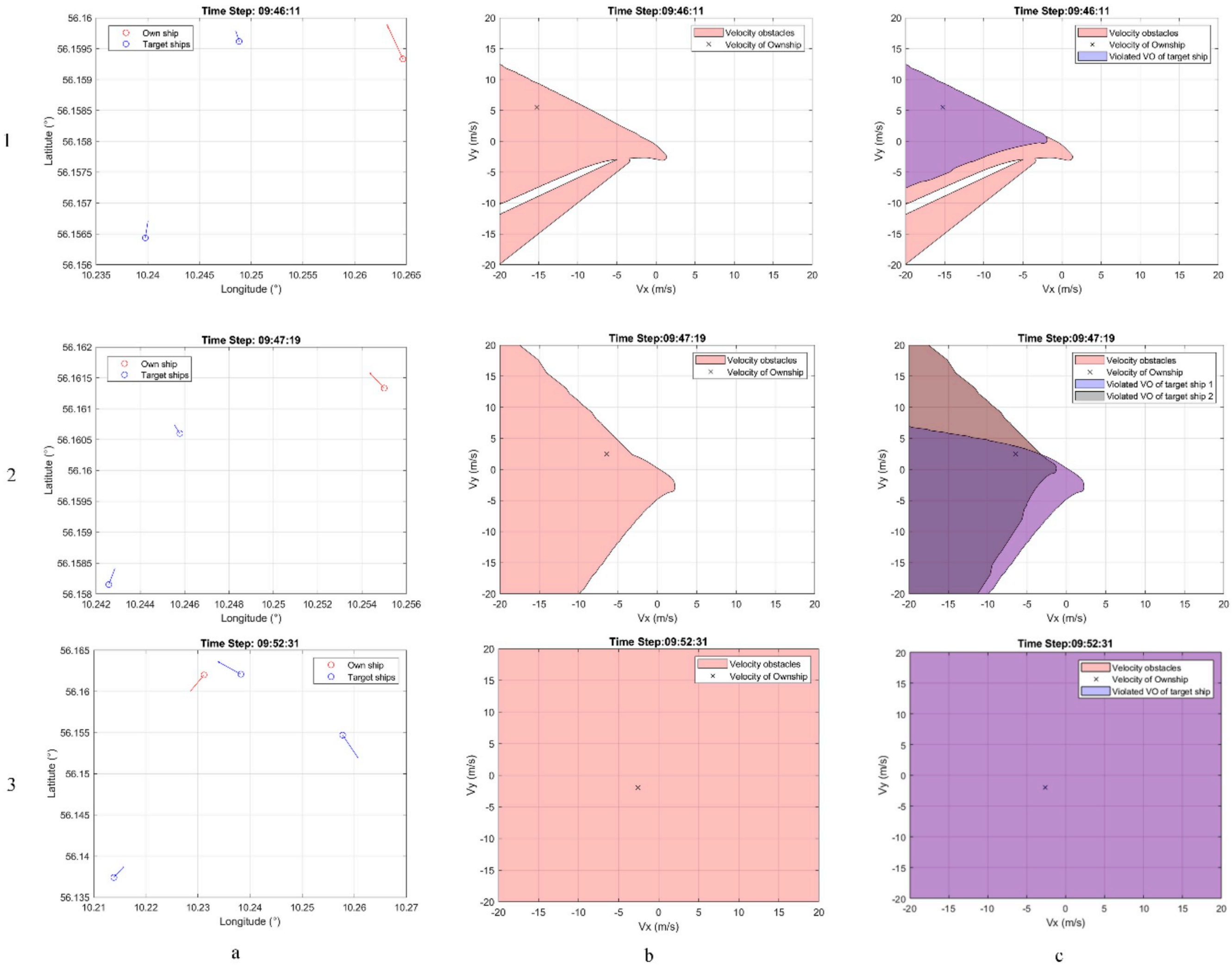


Fig. 4. Positions and VOs of ships at different time steps – scenario 1.

previous TD-NLVO is conducted from the design of the method and comparison of results, respectively. Besides, some detailed analysis of the union of VO sets are is also illustrated.

6.1. Validation

The essence of VO and its variations is to project the spatial-temporal relationships between ships into the velocity domain of the own ship. It provides a different perspective to interpret the encounter situation, which does not change the nature of the encounter. Therefore, one of the alternatives to verify the validity of the proposed method is to determine if the process of encounter also contains a period of time when the parameter such as DCPA violates the pre-set threshold. we utilized the traditional indicators Distance to Closest Point of Approach (DCPA), the relative distances and the TCPA on the two case studies to verify the validity of the proposed method. The results are shown in Figs. 6 and 7, respectively:

As can be seen from Figs. 6 and 7, all the indicators (DCPA, TCPA, and relative distance) fluctuate during the encounter process. As for encounter case 1, at time step 09:46:11 the DCPA between the own ship and target ship “578XXX000” is below the threshold while the corresponding TCPA and relative distance are above the threshold. These results indicate that the own ship and “578XXX000” could reach closer than threshold if they perform no avoidance manoeuvre, which is in consistence with the content in Fig. 4(1,b) and 4(1,c). At time step 09:47:19, both the DCPA between own ship and target ship “578XXX000” and “304XXX000” violate the threshold, while their TCPAs are positive, which indicate that the own ship will reach closer than threshold between both of them if they perform no avoidance manoeuvre, which is also in consistence with the content in Fig. 4(2,b) and 4(2,c). As for time step 09:52:31, the DCPA, TCPA, and relative distance between own ship and target “304XXX000” are all below the threshold, which indicate they have pass clear from each other, as for the own ship and target “578XXX000”, although the TCPA is negative, the relative distance between them is less than 500 m, which indicate they violate the pre-set safety boundary, which is still in consistence with the content in Fig. 4(3,b) and 4(3,c). As for encounter scenario 2, similar results can be interpreted from the figures. One thing should be noted is that the indicators fluctuate significantly during the encounter process, which is also presented in (Huang and Gelder, 2017)) with the help of simulations. As the previous research (Chen et al., 2018b) indicates that such process could be detected for multiple times if the encounter situation is analysed at certain time interval, instead of the whole process. Fig. 7 shows that although the DCPAs fluctuate significantly, their relative distances still smoothly reduce and then increase, which indicate that the encounter belongs to one process. Based on the comparison between traditional indicators and improved TD-NLVO, the validity of the proposed method is verified.

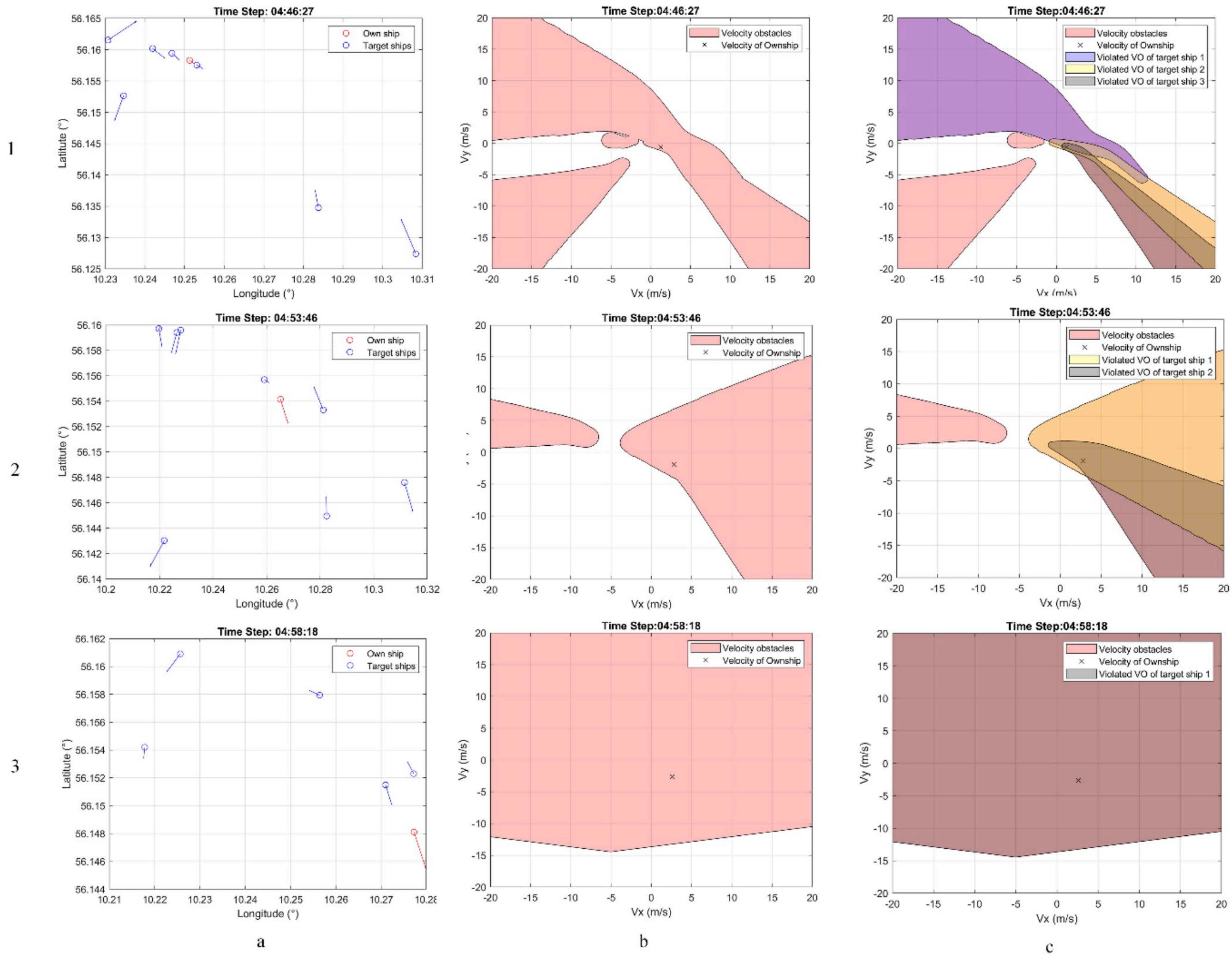


Fig. 5. Positions and VOs of ships at different time steps – scenario 2.

Table 3
Description of individual VO violations – scenario 2.

No.	MMSI of VO violation	Detection period	Description
1	219XXX000, 219XXX903	04:45:07 to 04:50:33	Individual violation
2	219XXX000, 231XXX000	04:45:07 to 04:55:47	Individual violation
3	219XXX000, 304XXX000	04:45:07 to 04:58:18	Individual violation
4	219XXX000, 219XXX903, 231XXX000, 304XXX000,	04:45:07 to 04:50:33	Four ships violation
5	219XXX000, 231XXX000, 304XXX000	04:50:37 to 04:55:47	Three ships violation
6	219XXX000, 304XXX000,	04:55:57 to 04:58:18	Individual violation

Table 4
Multi-ship encounter obtained with the improved method.

No.	Ships involved	Start time	End time
1	2497XXX00,2188XXX00,2587XXX00	15/10/2018 14:16:07	15/10/2018 14:16:31
2	2497XXX00,2188XXX00,2588XXX00	15/10/2018 14:20:44	15/10/2018 14:21:07
3	2588XXX00,2190XXX77,2587XXX00	15/10/2018 14:19:19	15/10/2018 14:24:15
4	2497XXX00,2188XXX00,2190XXX72	15/10/2018 14:31:41	15/10/2018 14:44:43
5	2497XXX00,2188XXX00,2190XXX72	15/10/2018 14:45:03	15/10/2018 14:46:03
6	2579XXX00,2091XXX00,2190XXX03	15/10/2018 15:49:29	15/10/2018 15:52:21

6.2. Comparison between the previous and the improved TD-NLVO

In the previous work by the authors (Chen et al., 2018b), the VO sets of own ship induced by target ship at certain time step are represented as a family of discrete VOs, which is shown in Fig. 8 (a). This is caused by the discrete nature of historical AIS data, i.e. for each data point of target ship which is later than the detection time step, a VO is calculated and is collected into the VO sets for further violation analysis. The advantages of doing so are related to the simplicity of implementation, however, such procedure also introduced redundant calculation burden of violation detection at each time step. For each discrete VO in the NLVO set, it must be determined if the velocity of own ship falls into this NLVO, or not. One solution to this problem is to first combine the discrete VOs as one united shape, which is the actual NLVO of the own ship induced by the target, and then utilize this combined NLVO to perform collision candidate detection, e.g. the combined NLVO shown in Fig. 8 (b). To do this, the Boolean operation on the polygon in section 3.2 is introduced. The advantages of such procedure are as follows: 1) compared with the previous TD-NLVO, the combined NLVO is more intuitive to understand the criterion of collision candidate. 2) For each time step of detection, only one determination of NLVO violation must be performed.

Another improvement in this work is the consideration of multiple ship encounter scenarios in collision candidate detection. To realize the

Table 5
Corresponding data obtained with previous TD-NLVO with each ship as own ship.

No.	Own ship	Target ship	Start time	End time
1	2497XXX00	2188XXX00	15/10/2018 14:15:00	15/10/2018 14:29:54
	2497XXX00	2587XXX00	15/10/2018 14:16:07	15/10/2018 14:16:31
2	2497XXX00	2588XXX00	15/10/2018 14:20:44	15/10/2018 14:21:07
	2497XXX00	2188XXX00	15/10/2018 14:15:00	15/10/2018 14:29:54
3	2588XXX00	2190XXX77	15/10/2018 14:19:19	15/10/2018 14:23:26
	2588XXX00	2587XXX00	15/10/2018 14:16:19	15/10/2018 14:29:49
	2587XXX00	2588XX000	15/10/2018 14:24:15	15/10/2018 14:29:41
4	2497XXX00	2188XXX00	15/10/2018 14:30:00	15/10/2018 14:44:43
	2497XXX00	2190XXX72	15/10/2018 14:31:37	15/10/2018 14:44:43
	2188XXX00	2497XXX00	15/10/2018 14:34:16	15/10/2018 14:44:46
5	2497XXX00	2188XXX00	15/10/2018 14:45:03	15/10/2018 14:46:03
	2497XXX00	2190XXX72	15/10/2018 14:45:03	15/10/2018 14:46:10
6	2579XXX00	2091XXX00	15/10/2018 15:49:29	15/10/2018 15:53:41
	2579XXX00	2190XXX03	15/10/2018 15:48:04	15/10/2018 15:52:21

functionality to detect the multiple ship encounter, the Boolean operation is utilized again to combine the VOs induced by each target ships at each detection time step; To make the comparison between the functionality of the core algorithm between the previous TD-NLVO and the improved version in this research, The case 1 is processed with the TD-NLVO. The results are shown in Table 6 and Fig. 9, respectively.

One can notice in Table 6 that the detection of the individual NLVOs is the same as results in Table 2. This is reasonable because of the same NLVO approach utilized in the two algorithms. However, as indicated in Table 6, the TD-NLVO is incapable of detecting the multiple ship encounter situation due to the decomposition process, as indicated in Fig. 9. Such a design also could lead to misinterpretation, e.g. in Fig. 9 ships 3 case, the figure shows that there is space outside the VO that the own ship is safe to choose. Actually it is otherwise because one large VO is not included in the figure.

Based on the comparison between the previous TD-NLVO and the improved core algorithm, the advantage the improved method are as follows: 1) the encounter situation is considered as a whole in the form of combined NLVO(s). 2) For the combined NLVO(s), firstly the violation of NLVO, i.e. collision candidate, can be determined, secondly, with the individual NLVO of each target ship, the participant which contributes to such a violation, their duration in detection time and other information, e.g. ship name, ship particulars, etc. can be furtherly obtained.

However, there are also some disadvantages of the proposed algorithm: 1) due to the union operation of individual VO induced by each data point of the target ship, the estimated duration of VO violation is no longer available in this new algorithm. 2) Due to the computational load on the Boolean operations, the time of calculation is increased to a certain extent, e.g. for current not-optimized algorithm it would take hours to process the one-day dataset. As for point 1), since the goal of the algorithm is to detect the collision candidate and multiple ship encounter situation, and such algorithm does not measure the actual distance between ships, the omission of this information is acceptable. As for point 2), the computational time can be improved with the trade-off between the accuracy on promoting the ConfP with points of polygon and optimization on the efficiency of the program, e.g. introducing a data compression algorithm such as Douglas-Peucker algorithm to accelerate the computation speed while maintaining the accuracy of the computation.

6.3. Detailed analysis of the union of NLVO sets

For a ship having encounters with multiple target ships, each target

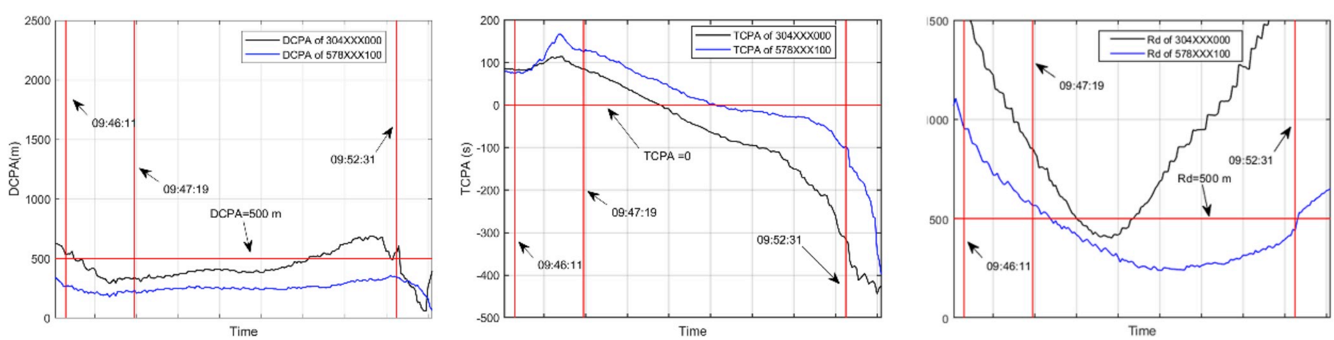


Fig. 6. DCPA, TCPA, and relative distance of encounter scenario 1.

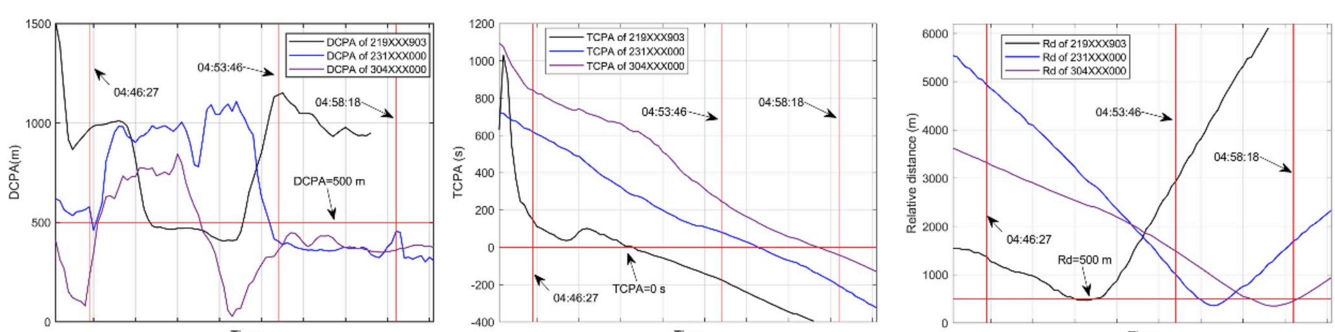
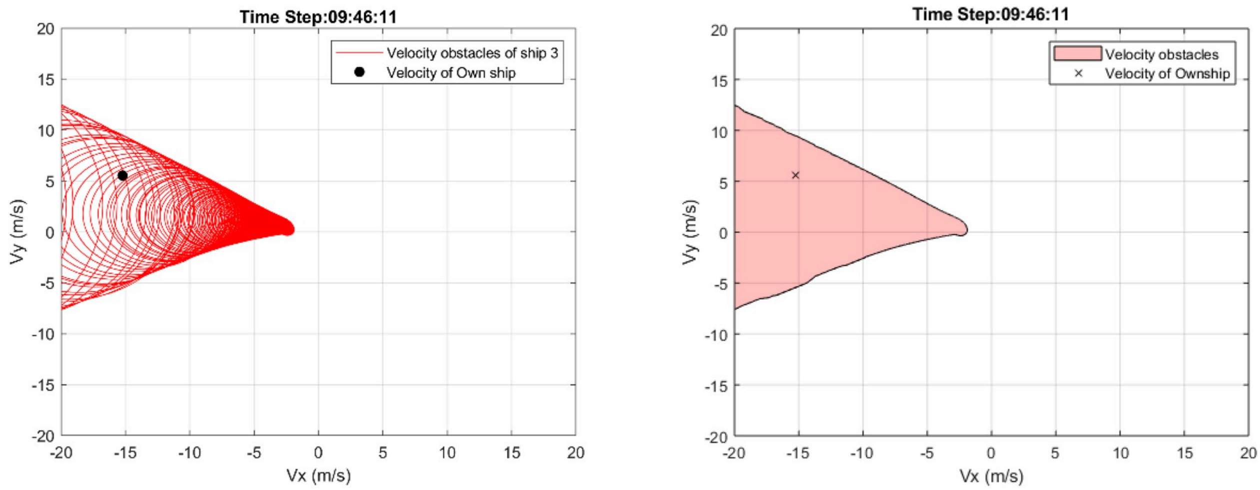


Fig. 7. DCPA, TCPA, and relative distance of encounter scenario 2.



(a) (b)

Fig. 8. Comparison between the improved algorithm (b) and TD-NLVO (a) on an individual encounter.

Table 6
Results of the case obtained with TD-NLVO.

No.	MMSI of VO violation	Detection period
1	219XXX000, 219XXX903	04:45:07 to 04:50:33
2	219XXX000, 231XXX000	04:45:07 to 04:55:47
3	219XXX000, 304XXX000	04:45:07 to 04:58:18

ship will induce an individual NLVO at the detection time. Boolean operation among these individual NLVOs is performed to obtain the combined NLVO which can reflect the encounter situation in the velocity domain of the own ship. During this process, multiple scenarios could happen, which are illustrated in Fig. 10, respectively:

Fig. 10 illustrates the examples of four typical combined NLVOs which are detected by the algorithm: 1) One combined NLVO where the contour of it is the largest individual NLVO and other individual NLVOs are “absorbed” within; 2) One combined NLVO where the contour of it is the combination of certain individual NLVOs; 3) multiple combined NLVO where individual NLVOs are combined into multiple groups; and 4) One combined NLVO where there is one or multiple “holes” inside. For scenario 1), 2) and 3) it is easy to determine if the velocity of own ship falls into the one of combined NLVO(s) or not, however, for scenario 4), it is otherwise. Due to the complicated situations when individual NLVOs overlapping with each other, in certain cases that within the combined NLVO, there will be certain regions where the velocity within the region are “safe” for the own ship to choose, i.e. if the velocity of own ship falls into the “hole” within the combined NLVO, the criterion of collision candidate will not be satisfied. Within the design of the algorithm, every polygon generated during the Boolean operation is stored separately. Therefore, there should be a method that can avoid potential false detection in this situation. We designed a criterion to avoid such false detection that only the situation where the velocity of the own ship falls into one of the combined polygons will be considered a violation of NLVO, i.e. for velocity of own ship that falls into the combined NLVO and the “hole” within at the same time, it will not be considered as a violation.

6.4. Potential for risk measurement of encounter scenarios

For probabilistic risk analysis of ship collision accident, identifying the encounters which have the potential for collision candidate is the first step (Fujii and Shiobara, 1971; Macduff, 1974). With the development of the methods for obtaining the collision candidate/near miss, not only the number of it, its characteristics, e.g. spatial-temporal distribution, composition in terms of indices such as ship type, etc. can be further analysed to facilitate decision making for stakeholders such as maritime safety authorities and port authorities to propose risk mitigation measures.

Moreover, the developed TD-NLVO method is capable for researchers to learn the time of the evasive action taken by the OOW, which might facilitate the researchers to analyse the distribution of time for taking evasive actions from historical AIS data and detects the abnormal behaviours based on the distribution(Du et al., 2019).

With the consideration of multiple-ship encounter situation during the collision candidate detection process, it provides a potential to measure the risk level of each encounter using the coverage of combined VOs, which is similar to the idea proposed by Huang et al. (Huang and van Gelder, 2019). Such potential can be further integrated with the analysis on causation probability of ship collision accident.

In the meantime, there are also some factors should be considered for the application of the proposed in collision risk analysis. Firstly, due to the diversity of the regional traffic characteristics, e.g. density and characteristics of the waterway, the criteria of collision candidate when applying the methods should consider the influence of these factors, to improve the accuracy and reliability of the results. one of the possible solutions to this issue would be to design a to design a flexible and fuzzy-based safety boundary as the safety region, i.e. a safety region which is based on the characteristics of the own ship, e.g. ship type, length, velocity, etc., and the traffic characteristics, e.g. density, complexity, etc. of the regional traffic into consideration. Ship domain and its variations (Szlapczynski and Szlapczynska, 2016: Szlapczynski and Szlapczynska, 2017), e.g. Fuzzy Ship domain (Zhou and Zheng, 2019), Quaternion ship domain (Wang, 2010), etc. can be a good starting point to conduct the research. However, according to the experience of the authors, with more complicated shape introduced, the computing burden is growing, the method to accelerate the computation should also be considered to improve the efficiency of the algorithm. Besides, although with consideration of the multi-ship encounter situations into the risk analysis in waterways, the deeper insights can be obtained, in terms of simple and complicated encounter and information about their characteristics, e.g. spatial-temporal distribution, etc., within the multi-ship encounter, a prioritization could also be considered to extract the information on which type of behaviour in the waterways could contribute more to the risk of collision, to achieve such objective, some analysis of

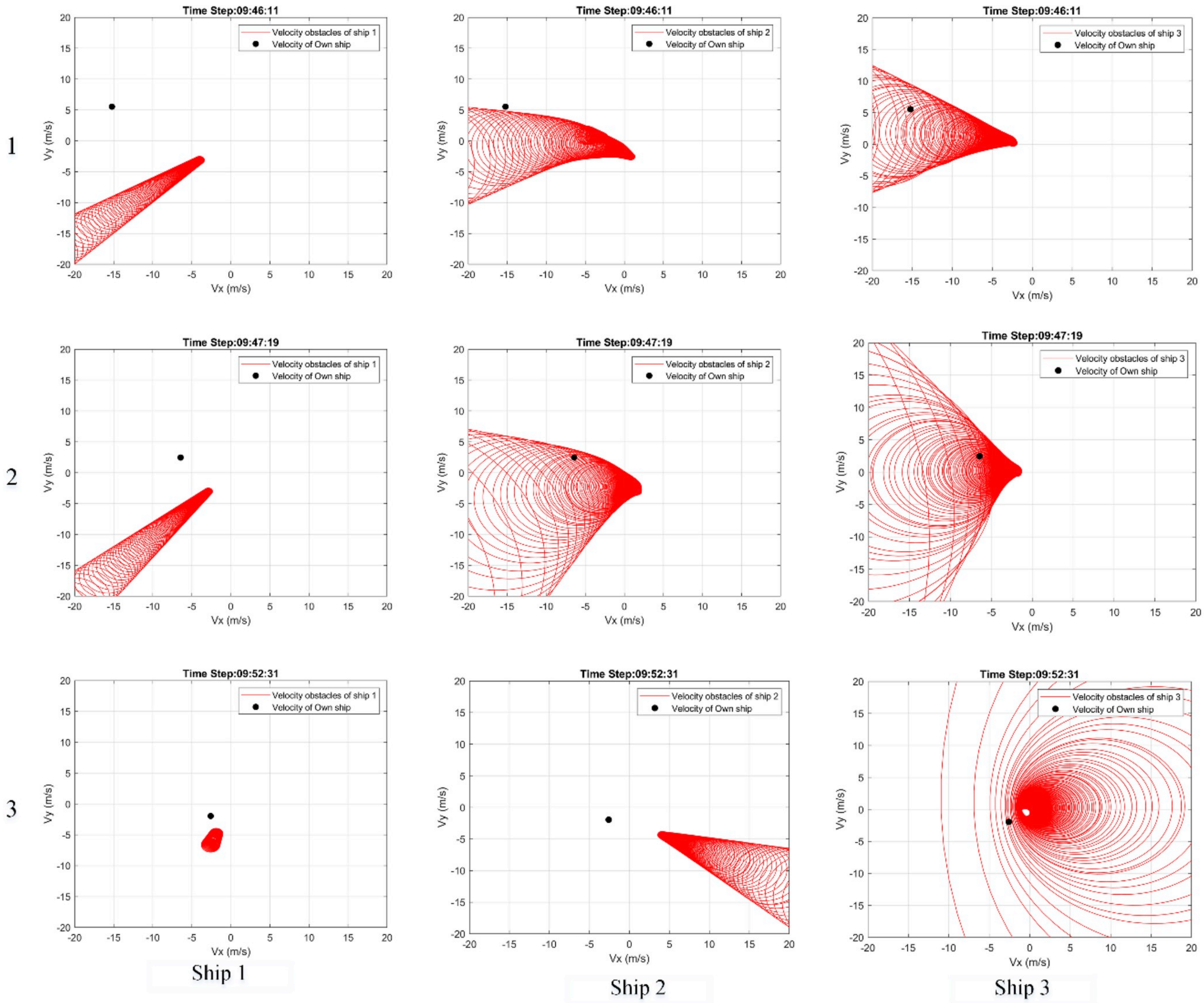


Fig. 9. Examples of case 1 obtained with the previous TD-NLVO.

traditional indicators, e.g. CPA, can be utilized.

Secondly, for collision risk analysis in the waterways, collision candidate analysis, or encounter analysis is only one step towards to comprehensive risk analysis, i.e. the analysis of this step only provides the results on which encounter have the potential for collision, based on the indicators of spatial-temporal proximity between ships. Another aspect, that is the causal factors, should also be considered in the analysis process, to obtain the deeper insights on which encounter situation is more likely to results in an accident. To achieve this goal, various methods can be introduced, e.g. Fault Tree Analysis (FTA), Bayesian Network (BN) (Hänninen, 2014) and its variations, e.g. Credal Network (CN) (Chen et al., 2019b; Zhang et al., 2018) can be a good starting point to integrate the information for risk analysis.

6.5. Application of the improved TD-NLVO on collision candidate detection and collision avoidance

In the previous sections, the core algorithm for detecting multiple ship encounter process using the improved TD-NLVO combined with Boolean operation on polygons has been proposed. The two case studies also illustrate the capability of the core algorithm and some typical situations when combining the individual NLVOs are also presented. The results indicate that this method is capable of detecting the multiple ship encounter and has the potential to be utilized for an estimate the geometric probability for ship collision risk analysis and provide detailed analysis on the encounters that satisfied the pre-set criteria. However, due to the limited access of AIS data in our research, only the open and free access to historical AIS data provided by the Danish Maritime Authority are introduced to verify the algorithm. We note that there is an area-related influence on our findings due to navigational conditions which in some situations could result in different results.

As for the application of the improved TD-NLVO on estimating the number of collision candidate, there are some issues that need further research: 1) How to deal with the complicated situation where own ship has multiple NLVO violations with target ships at different time steps? For the situation where the own ship has NLVO violation with one target ship and meanwhile another NLVO violation occurred within the duration of the previous one, e.g. the situation demonstrated in case 2, where the own ship has multiple violations of individual NLVOs at a certain period of time and the participators were dynamically varying. 2) Definition of collision candidate. For the previous researches, the collision candidate usually refers to pairs of encountered ships that satisfied the pre-set criteria. However, such a definition would not be suitable when taking the multiple ship encounter into consideration. Since the goal of this paper is to propose the core algorithm for detecting the multiple ship encounters, these issues will be the research questions

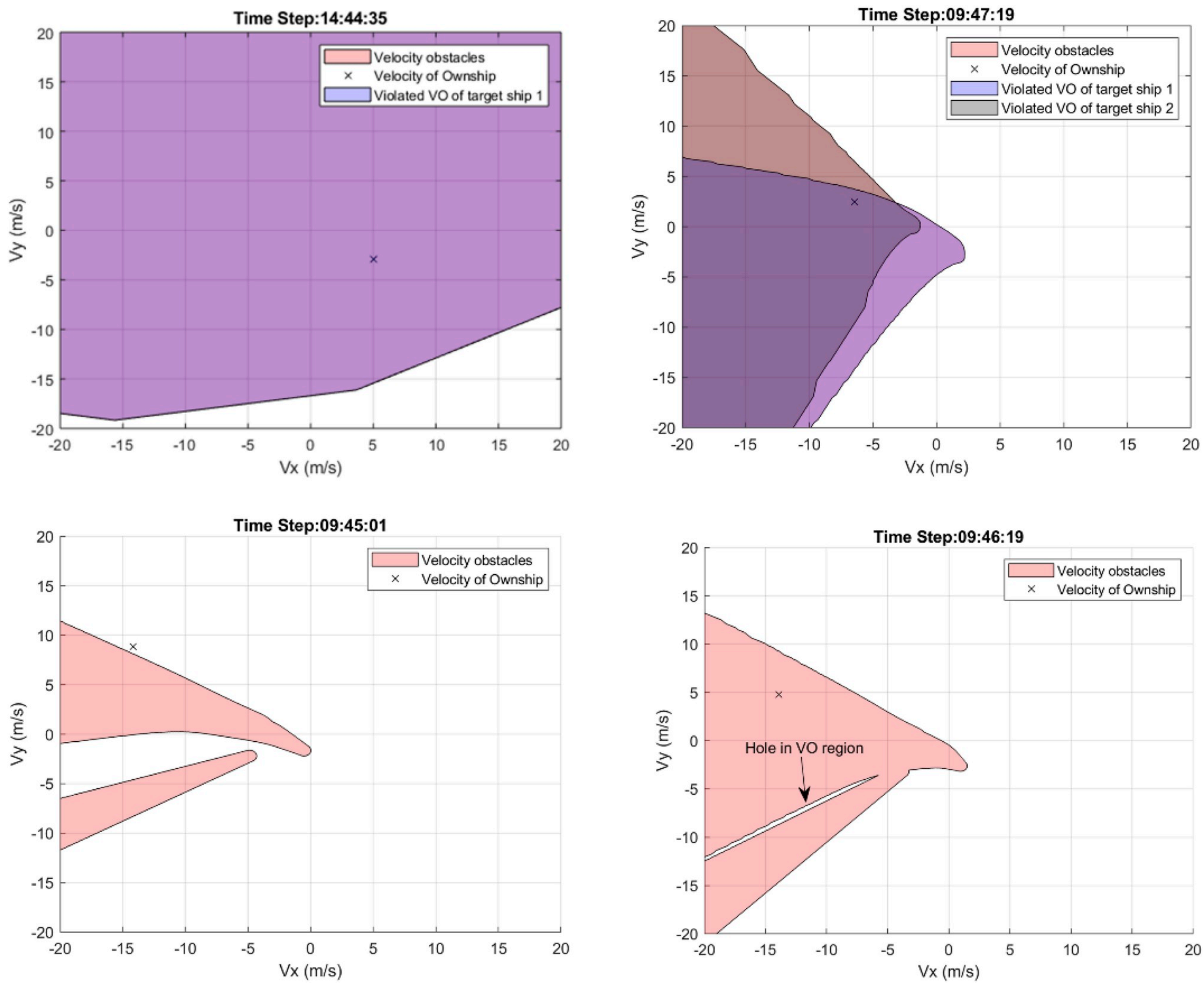


Fig. 10. Example of four combined situations when performing the Boolean operation on individual NLVOs.

for future work.

The velocity-based approaches have already been applied in the collision risk analysis and collision avoidance research, although which have not been formally defined as Velocity Obstacle-based approach before (Fiorini and Shiller, 1998), e.g. the concept of Collision Threat Parameter Area (CTPA) (Lenart, 1983) and the traffic conflict technique proposed by van Westrenen et al. (Westrenen and Baldauf, 2019; van Westrenen and Ellerbroek, 2017) which are equivalent to Linear-Velocity Obstacle (LVO) method. From these researches, the capability of velocity-based approach on detecting collision candidate and risk of collision is shown. Although the objective of this research is to propose an improved version of TD-NLVO for ship collision candidate detection for risk analysis in waterways, the proposed methods also have the potential for application in collision avoidance for individual ship, e.g. autonomous ship, also known as Maritime Autonomous Surface Ship (MASS). For collision avoidance of individual ships, the process usually contains two steps: 1) conflict detection, which is to determine if the risk exists; and 2) conflict resolution, which is to determine the collision-free solution and control the ship to safely execute the solution (Huang et al., 2019a). The proposed method, together with its variations, e.g. GVO (Huang et al., 2019b) can facilitate the Officer on Watch (OOW) or the controller on MASS to identify the potential risk of collision. In the meantime, these methods can also provide more intuitive conflict resolution proposals to the controller of the own ship to avoid the collision, i.e. the solution can be given in the form of the desired velocity (speed and course) change, with facilitation of considering the ship dynamic during the process. As for the development of VO in this direction, Huang et al. have conducted extensive research on application VO algorithm on collision avoidance, e.g. (Huang et al., 2018, 2019b), where the GVO is utilized to conduct the collision avoidance of autonomous ship in a cooperative multi-ship situation and a solution for collision avoidance in multi-ship encounter situation is proposed: 1) ships broadcast their trajectory information sequentially; 2) the own ship chooses collision avoidance solution and broadcast the updated trajectory; 3) the next ship updates its own trajectory information based on the new inputs; 4) repeat the process until all the ships find their solution. Chen et al. (2019a) also proposed a cooperative multi-ship system for the urban waterway network where velocity obstacle method are utilized as a benchmark. Considering these developments of VO and its variations, we think it is also promising to utilize VO for future collision avoidance facilitation of MASS.

7. Conclusion

Analysing ship encounters and identifying collision candidates or near misses that have the potential for ship collision accident is a critical element for quantitative risk analysis of ship collision. To do this, various approaches have been proposed. In this paper, based on the previous work on Time Discrete Nonlinear Velocity Obstacle (TD-NLVO) method, an improved multiple ship encounter detection algorithm is proposed.

To overcome the discrete nature of historical Automatic Identification System (AIS) data and its influence on the velocity obstacles, the Boolean operation on polygons is introduced to combine the Non-Linear Velocity Obstacles (VOs) induced by the target ship at each data point. Based on the union operation, an integral NLVO for each individual target ship is generated. The consideration of multiple ships when performing the detection is achieved in a similar manner. With such improvement, the multiple ship encounter situation can be considered as a whole, instead of decomposing such situation into multiple two-ship encounter scenarios.

Two sets of AIS data were utilized as test data to verify the effectiveness of the proposed methods. the results indicate that the Boolean operation on the individual NLVOs has successfully combined them as a whole, and the algorithm is capable of detecting the violation of the combined NLVO, as well as the individual violations. Based on the results, the multiple encounter situation is also identified.

A comparison between the previous TD-NLVO and the proposed method is conducted, and it shows that the combined NLVO set is intuitive to understand and reduced the redundant calculations. Moreover, potential scenarios of combined NLVOs are illustrated and analysed. A simple method to avoid potential false identification due to "holes" in the combined NLVO is proposed and implemented in the algorithm.

With this improved TD-NLVO, the multiple ship encounters that satisfied the pre-set criteria for collision candidate can be detected using the historical AIS data, which has the potential to be utilized for estimation of geometric probability for ship collision risk analysis. However, further research on determining the number of collision candidates considering the complicated multiple ship scenario should be made in the future.

With the improvement in this research, it provides a potential for new risk measurement of encounter situations where the coverage of the combined NLVO can be utilized as an indicator (Huang and van Gelder, 2019). The proposed method provides a new perspective to consider multiple encounter situation, which can provide more detailed information to the relevant stakeholders, e.g. port authorities and maritime safety administration, etc. to understand the collision risk in the region and facilitate the decision-making process of safety measures. In the meantime, to conduct a more comprehensive risk analysis of ship collision accident in the waterways, the consequence aspects could also be integrated as an indicator that reflects the level of severity of the accident. To do so, more research on the ship structure, energy of collision, and etc., could be utilized.

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Appendix. Glossary of variables

Variable	Definition
VO	Velocity Obstacle
NLVO	Non-linear Velocity Obstacle
L	Length of ship
P	Position of ship
V	Velocity of ship
ConfP	Conflict Position
R	The radius of the Conflict Position
t	Time
t_0	Starting time
t_i	Any given time
t_C	Time of collision

References

Baksh, A., Abbassi, R., Garaniya, V., Khan, F., 2018. Marine transportation risk assessment using Bayesian Network: application to Arctic waters. Ocean Eng. 159, 422–436.
Chai, T., Weng, J.X., Xiong, D.Q., 2017. Development of a quantitative risk assessment model for ship collisions in fairways. Saf. Sci. 91, 71–83.
Chen, L., Huang, Y., Zheng, H., Hopman, H., Negenborn, R., 2019. Cooperative multi-vessel systems in urban waterway networks. IEEE Trans. Intell. Transp. Syst. 1–14.
Chen, P., Huang, Y., Mou, J., van Gelder, P.H.A.J.M., 2019. Probabilistic risk analysis for ship-ship collision: state-of-the-art. Saf. Sci. 117, 108–122.
Chen, P., Mou, J., van Gelder, P.H.A.J.M., 2019. Integration of individual encounter information into causation probability modelling of ship collision accidents. Saf. Sci. 120, 636–651.
Chen, P.F., Huang, Y.M., Mou, J.M., van Gelder, P.H.A.J.M., 2018. Ship collision candidate detection method: a velocity obstacle approach. Ocean Eng. 170, 186–198.
Debnath, A.K., Chin, H.C., 2016. Modelling collision potentials in port anchorages: application of the navigational traffic conflict technique (NTCT). J. Navig. 69 (01), 183–196.
Du, L., Goerlandt, F., Banda, O.A.V., Huang, Y., Wen, Y., Kujala, P., 2019. Improving stand-on ship's situational awareness: a non-linear velocity obstacle (NL-VO) algorithm approach. Ocean Eng. (Under review).
EMSA, 2017. Annual Overview of Marine Casualities and Incidents 2017. European Maritime Safety Agency.
Fang, Z.X., Yu, H.C., Ke, R.X., Shaw, S.L., Peng, G.J., 2019. Automatic identification system-based approach for assessing the near-miss collision risk dynamics of ships in ports. IEEE Trans. Intell. Transp. Syst. 20 (2), 534–543.
Fiorini, P., Shiller, Z., 1998. Motion planning in dynamic environments using velocity obstacles. Int. J. Robot. Res. 17 (7), 760–772.
Fujii, Y., Shiobara, R., 1971. The analysis of traffic accidents. J. Navig. 24 (04), 534–543.
Goerlandt, F., Kujala, P., 2011. Traffic simulation based ship collision probability modeling. Reliab. Eng. Syst. Saf. 96 (1), 91–107.
Goerlandt, F., Montewka, J., 2014. A probabilistic model for accidental cargo oil outflow from product tankers in a ship-ship collision. Mar. Pollut. Bull. 79 (1–2), 130–144.
Goerlandt, F., Montewka, J., 2015. A framework for risk analysis of maritime transportation systems: a case study for oil spill from tankers in a ship–ship collision. Saf. Sci. 76, 42–66.
Hänninen, M., 2014. Bayesian networks for maritime traffic accident prevention: benefits and challenges. Accident Analysis & Prevention 73, 305–312.
Huang, Y., Chen, L., Chen, P., Gelder, P.v., 2019. Ship Collision Avoidance Methods: State-Of-The-Art. Safety Science (Under review).
Huang, Y., Chen, L., van Gelder, P.H.A.J.M., 2019. Generalized velocity obstacle algorithm for preventing ship collisions at sea. Ocean Eng. 173, 142–156.
Huang, Y., van Gelder, P.H.A.J.M., 2017. Non-linear velocity obstacles with applications to the maritime domain. In: Soares, G., Teixeira (Eds.), The 17th International Congress on Maritime Transportation and Harvesting of Sea Resources. Taylor & Francis Group, Lisbon, Portugal, pp. 999–1007.
Huang, Y., van Gelder, P., 2019. Time-varying risk measurement for ship collision prevention. Risk Anal.
Huang, Y., van Gelder, P.H.A.J.M., Wen, Y., 2018. Velocity obstacle algorithms for collision prevention at sea. Ocean Eng. 151, 308–321.

Lenart, A.S., 1983. Collision Threat parameters for a new radar display and plot technique. J. Navig. 36 (3), 404–410.

Lenart, A.S., 2015. Analysis of collision Threat parameters and criteria. J. Navig. 68 (05), 887–896.

Macduff, T., 1974. The probability of vessel collisions. Ocean Ind. 9 (9).

Martínez, F., Rueda, A.J., Feito, F.R., 2009. A new algorithm for computing Boolean operations on polygons. Comput. Geosci. 35 (6), 1177–1185.

Montewka, J., Hinz, T., Kujala, P., Matusiak, J., 2010. Probability modelling of vessel collisions. Reliab. Eng. Syst. Saf. 95 (5), 573–589.

Pedersen, P.T., 1995. Collision and grounding mechanics. In: Proceedings of WEMT, 95, pp. 125–157, 1995.

Szlapczynski, R., Szlapczynska, J., 2016. An analysis of domain-based ship collision risk parameters. Ocean Eng. 126, 47–56.

Szlapczynski, R., Szlapczynska, J., 2017. Review of ship safety domains: Models and applications. Ocean Engineering 145, 277–289.

van Westrenen, F., Ellerbroek, J., 2017. The effect of traffic complexity on the development of near misses on the North sea. IEEE Trans. Syst. Man Cybern.: Systems 47 (3), 432–440.

Wang, N., 2010. An intelligent spatial collision risk based on the quaternion ship domain. The Journal of Navigation 63 (4), 733–749.

Wen, Y., Huang, Y., Zhou, C., Yang, J., Xiao, C., Wu, X., 2015. Modelling of marine traffic flow complexity. Ocean Eng. 104, 500–510.

Westrenen van, F., Baldauf, M., 2019. Improving conflicts detection in maritime traffic: Case studies on the effect of traffic complexity on ship collisions. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 1475090219845975.

Zhang, W.B., Kopca, C., Tang, J.J., Ma, D.F., Wang, Y.H., 2017. A systematic approach for collision risk analysis based on AIS data. J. Navig. 70 (5), 1117–1132.

Zhao, M., Yao, X., Sun, J., Zhang, S., Bai, J., 2019. GIS-based simulation methodology for evaluating ship encounters probability to improve maritime traffic safety. IEEE Trans. Intell. Transp. Syst. 20 (1), 323–337.

Zhang, G., Thai, V.V., Yuen, K.F., Loh, H.S., Zhou, Q., 2018. Addressing the epistemic uncertainty in maritime accidents modelling using Bayesian network with interval probabilities. Safety science 102, 211–225.

Zhao, Y., Li, W., Shi, P., 2016. A real-time collision avoidance learning system for Unmanned Surface Vessels. Neurocomputing 182, 255–266.

Zhen, R., Riveiro, M., Jin, Y.X., 2017. A novel analytic framework of real-time multi-vessel collision risk assessment for maritime traffic surveillance. Ocean Eng. 145, 492–501.

Zhou, D., Zheng, Z., 2019. Dynamic Fuzzy Ship Domain Considering the Factors of Own Ship and Other Ships. The Journal of Navigation 72 (2), 467–482.