Improving stand-on ship's situational awareness by estimating the intention of the give-way ship

Du, Lei; Goerlandt, Floris; Valdez Banda, Osiris A.; Huang, Yamin; Wen, Yuanqiao; Kujala, Pentti

DOI
10.1016/j.oceaneng.2020.107110

Publication date
2020

Document Version
Final published version

Published in
Ocean Engineering

Ocean Engineering 201 (2020) 107110

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Improving stand-on ship's situational awareness by estimating the intention of the give-way ship

Lei Du [a], Floris Goerlandt [b], Osiris A. Valdez Banda [a], Yamin Huang [c,d,e,*], Yuanqiao Wen [c,d], Pentti Kujala [a]

[a] Aalto University, School of Engineering, Department of Mechanical Engineering, Espoo, Finland
[b] Dalhousie University, Department of Industrial Engineering, Halifax, Nova Scotia, B3H 4R2, Canada
[c] National Engineering Research Center for Water Transport Safety (WTSC), Wuhan, China
[d] Wuhan University of Technology, Intelligent Transportation System Research Center, Wuhan, China
[e] Delft University of Technology, Policy and Management, Faculty of Technology, Delft, the Netherlands

ARTICLE INFO

Keywords:
Situational awareness
Second line of defense (SLoD)
Conflict
Ship intention
Non-linear velocity obstacles (NL-VO) algorithm
Action uncertainty

ABSTRACT

The lack of situational awareness is a major cause of ship collisions. Thus, enhancing the situational awareness of the stand-on ship is a key for navigational safety, where the intention estimation of the give-way ship is crucial. According to COLREGs, the stand-on ship is not allowed to take evasive actions until the give-way ship does not take proper actions timely. The stage that needs the stand-on ship to take actions plays as the second protective layer for the ship, which is named as 'Stand-on Ship as Second Line of Defense' (SLoD). A method to estimate the intention of the give-way ship and to trigger SLoD is proposed in this article. Four modules of the proposed method include: "data pre-processing" collects all traffic information and determines the ships' obligations; "action identification" pinpoints the turning points; "action uncertainty" generates a bounded reachable velocity considering the give-way ship's maneuverability; "conflict assessment" judges potential collision by using non-linear velocity obstacle algorithm. Several typical encounter scenarios are simulated to demonstrate the feasibility of the proposed method. The results show that intention estimation of the give-way ship improves the situational awareness of the stand-on ship, which can support the stand-on ship to make collision avoidance decisions.

1. Introduction

1.1. Background

The occurrence of marine casualties and incidents still remains stable at a high level (around 3400 per year), of which ship collisions account for a substantial portion (23.2%) (EMSA, 2018). Research suggests that in many collision cases, a lack of situational awareness is one of the main contributing factors in ship collisions (Liu and Wu, 2004; Gale and Patraiko, 2007).

The International Regulations for Preventing Collision at Sea (COLREGs) is an efficient system of rules for enhancing the ship's situational awareness. The COLREGs has clearly described the obligations of ships at different stages of collision, but it does not provide specific guideline to set the boundaries of different stages (Zhang et al., 2012; He et al., 2017). It might not be a problem for the give-way ship since her obligation is explicit and constant, while that of the stand-on ship is varying at different stages. A stand-on ship is required to keep her course and speed at the beginning of the encounter, while the obligations of the ship changes if some conditions are met. Specifically, the stand-on ship **is permitted to act** when there is evidence that the give-way ship does not act properly or legally, while the stand-on ship **shall act** if the ship collision cannot be avoided by the give-way ship's action alone, according to Rule 17 in the COLREGs.

A clear guideline to delineate each encounter stage for the stand-on ship is crucial and necessary. However, such guidelines are missing in the COLREGs. In practice, the judgements of different stages mainly rely on navigators' experience. Due to the various interpretations of the different stages by different navigators, it is difficult to determine the exact thresholds for the different stages (He et al., 2017). In many cases, these kinds of misinterpretations easily result in collisions. For instance, the stand-on ship may illegally act to master the situation when the rule

* Corresponding author. National Engineering Research Center for Water Transport Safety (WTSC), Wuhan, China.
E-mail addresses: y.m.huang@outlook.com, yaminhuang@whut.edu.cn (Y. Huang).

https://doi.org/10.1016/j.oceaneng.2020.107110
Received 5 April 2019; Received in revised form 31 December 2019; Accepted 10 February 2020
Available online 5 March 2020
0029-8018/

requires the ship to keep her course and speed in the initial stage of collision avoidance (Chauvin and Lardjane, 2008). Moreover, a clear delineation not only eliminates the misinterpretation between ships but also helps the stand-on ship to take timely action for avoiding accidents. For example, the collision between the oil tanker SANCHI and the bulk carrier CF CRYSTAL caused the sunk of SANCHI with deaths of 3 people and disappearance of 29 crews (China Maritime Safety Administration, 2018). This serious collision would have possibly been avoided, if the stand-on ship CF CRYSTAL could take effective evasive actions timely, even if the give-way ship SANCHI did not perform the duties of giving way. It is plausible that the effective response from a stand-on ship can significantly reduce the probability of ship collision. Therefore, there is of importance to improve the understanding of the stand-on ship's role during collision avoidance, and to develop methods to delineate the different encounter stages in terms of conflict.

Considerable research has been dedicated to improving the COLREGs' applicability in the maritime domain, including conflict analysis (Debnath and Chin, 2010; Goerlandt et al., 2012a). The conflict is defined as a situation of near collision which has great potential to be a collision (Lei et al., 2017), which is more frequently occurred at sea and overcomes the shortage of the low number of observations of the collision at specific sites (Du et al., 2019). However, to the best of the authors' knowledge, there is little focus on the stand-on ship's role in elimination of the ship conflict and few work focusing on quantifying the different stages of encounter from the stand-on ship's perspective in the literature. A detailed review has been shown in Section 2.1.

1.2. Motivation

The key for triggering the stand-on ship to act properly and legally is to make a correct judgement of the moment/stage for the stand-on ship to take actions, which is based on correctly inferring the intention of the give-way ship. In contrast to ship action prediction that is intended to predict what action a ship will take in the future, the ship intention estimation is to judge the motivation why the ship takes this action. In brief, the research question of this manuscript is that: How would the stand-on ship know the motivation of the behavior of the give-way ship and the stage of the encountering situation?

In this article, the stage that needs the stand-on ship to take action is named as 'Stand-on Ship as Second Line of Defense' (SLoD). The ship intention is estimated based on the observed ship's actions. The ship action in turn reflects the ship intention, which in encounter situations is related to conflict. The change of the ship's motion state is mainly determined by the ship action, and is also influenced by ship's maneuverability. To clarify the intended meaning of this key terminology, the definitions of SLoD, ship's intention, and ship action are defined as follows:

SLoD: A critical state that triggers the stand-on ship to take evasive action when the give-way ship does not take the proper evasive action timely in compliance with COLREGs, aiming to reduce the ship collision occurrence probability.

Ship intention: The motivation of the ship's actions, aimed at attaining navigational objectives, e.g., accident avoidance, route-following, etc.

Ship action: The changes of speed or/and course under the effects of human's action of manned ship or automation systems in autonomous ship, which is also limited by the ship maneuverability and environmental disturbance.

In the literature, many studies have been dedicated to eliminating conflict, e.g., (Blaich et al., 2012; Johansen et al., 2016; Szlapczynski and Krata, 2018; Huang et al., 2019; Montewka et al., 2010; Wu et al., 2020). However, many of them only propose the strategies of conflict elimination from the perspective of the give-way ship only, or without distinguishing the stand-on ship and the give-way ship. Additionally, only a few of researches attach importance to the vessel dynamics and the uncertainty related to the ship action. Lastly, ship intention of the give-way ship is usually out of considerations.

1.3. Contribution

Given the above, the principal aim of this article is to propose a method to estimate the intention of a give-way ship considering conflict. This method is intended to be used for improving the stand-on ships' situational awareness in good visibility condition in compliance with Rule 17 in COLREGs, which would contribute to the reduction of collision accidents. In brief, the contributions of this article are concluded as follows:

(1) A novel concept, SLoD, servicing for the stand-on ship to make action decision in elimination of conflict.
(2) A method to estimate the intention of the give-way ship incorporating the elimination of conflict of the give-way ship.

1.4. Outline

The remainder of this paper is arranged as follows. Section 2 is the literature review of this research. Section 3 elaborates on the methods adopted to quantitatively analyze ship intention. This method is applied to two designed ship encounter scenarios in Section 4 that analyzes the give-way ship's action and its corresponding intention. A discussion and some recommendations for future research are provided in Section 5. Section 6 concludes the findings.

2. Literature review

There are three protective layers of conflict depending on the obligation of taking evasive action, which corresponds to different levels of risk in compliance with COLREGs. As illustrated in Fig. 1, these are denoted 'Give-way ship as First Line of Defense' (FLoD), 'Stand-on Ship as Second Line of Defense' (SLoD), and 'Both ships as Third Line of Defense' (TLoD).

The first protective layer of elimination of conflict FLoD is constructed by the give-way ship, in which the stand-on ship is required to keep her course and speed unchanged in the initial stage of the existence of a conflict. However, if it is apparent that the give-way ship does not manoeuvre appropriately or even does not act according to Rule 17 in COLREGs, the stand-on ship's obligation for elimination of conflict is activated, which constructs the second layer SLoD. If the second protective layer SLoD is activated as the conflict cannot be avoided by the give-way ship's negative evasive action alone, both ships are required to act, which is the third layer TLoD.

2.1. COLREGs-compliant elimination of conflict from the stand-on ship's perspective

Some representative research on elimination of conflict is listed in Table 1. The green marked content is clearly stated in the text, while the yellow marked content is inferred from the description in the text. Much of the existing research propose the strategies of eliminating conflict from the give-way ship perspective only, or without distinguishing the stand-on ship or the give-way ship.

To our best knowledge, most work focuses on the construction of a FLoD. Zhuo and Tang (2008) proposed the LTTA to decide the last time for anti-collision action should be taken. The minimum distance required for anti-collision by only the give-way ship (under normal situations) is studied in Zhang et al. (2012). Montewka et al. applied MDTC to the collision avoidance decision making of give-way ship (Montewka and Przemyslak, 2014). The work (He et al., 2017) quantitatively analyzes the COLREGs and seamanship for autonomous collision avoidance at open sea, while the stand-on ship's action starting time is set

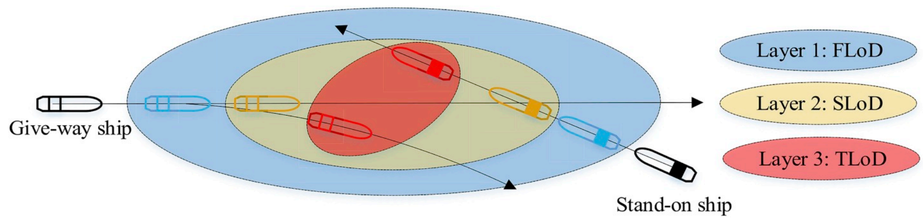

Fig. 1. Three protective layers of elimination of conflict in good visibility (shape and size of the layers for illustration purposes only).

Table 1
Representative works aiming at quantifying the COLREGs for eliminating conflict.

Paper	Protective layer	For give-way ship only	For stand-on ship only	For both ships	Action dynamic	Action uncertainty	Ship intention
Zhuo and Tang, 2008	FLoD	Certain					
Montewka et al., 2010	TLoD			Certain			
Zhang et al., 2012	FLoD+TLoD	Certain		Certain			
Montewka et al., 2014	FLOD	Certain					
Krata and Montewka, 2015	SLoD		Certain		Certain		
Johansen et al., 2016	FLoD/SLoD	Ambiguous	Ambiguous		Certain	Certain	
Baldauf et al., 2017	FLoD/SLoD	Ambiguous	Ambiguous			Certain	
He et al, 2017	FLoD	Certain					
Huang et al., 2018	FLoD	Certain			Certain	Certain	
Cho et al., 2018	FLoD/SLoD	Ambiguous	Ambiguous			Certain	Certain
Szlapczynski and Krata, 2018	FLoD/SLoD	Ambiguous	Ambiguous				

Note: Certain: (green) Ambiguous: (yellow)

subjectively. Huang et al. (2018) utilizes NL-VO to support navigator on the give-way ship to find a safe course. Nonetheless, these evasive actions are designed from the perspective of the give-way ship, and the stand-on ship's role in the collision avoidance is usually underestimated.

For supporting SLoD, the work done by Krata and Montewka (2015) defines the critical area for a maneuver of a stand-on ship, based on the assumption that the give-way ship continues with her course and speed during the encounter process. The dynamic nature of ship action is considered in this work, while the ship action uncertainty and ship intention are not discussed. Therefore, the stand-on ship's role needs more focus.

There is also some work analyzing the elimination of conflict from both ships' perspective, which aims at constructing TLoD. Montewka et al. (2010) applied MDTC to the collision avoidance decision making of two ships. Collectively, all these collision avoidance strategies heavily rely on ship maneuverability, while in the real-world it is hard to know the other ship's maneuverability. Moreover, the ship's maneuverability is dynamic under different encounter scenarios. The minimum distance required for safe passing with both two ships steering under critical situations is also analyzed in Zhang et al. (2012), which is based on an assumption that the two ships change their courses simultaneously to avoid collision without considering the dynamic and uncertainty nature of ship action.

The remaining four articles are intended to support the decision-making of ships that need to take evasive action, and therefore this is applicable for the stand-on ship or the give-way ship. A collision avoidance system for ships is also proposed, which is based on model predictive control and compliance with the COLREGs rules (Johansen et al., 2016). Baldauf et al. (2017) proposed the concept of the Last Line of Defense (LLoD) to trigger the "perfect warning" to avoid collision at sea. A collision avoidance solution for ship navigating in severe weather conditions is determined with ship stability and COLREGs considered (Szlapczynski and Krata, 2018). A strategy of ship collision avoidance by inferring ship intention is proposed in Cho et al. (2018).

However, the timing of the stand-on ship taking evasive action during the process of eliminating conflict is vital but still not been quantitative determined. For the MDTC, LTTA and LLoD, the ship taking evasive action before this deadline means the conflict can be avoidable. For the stand-on ship, taking action too late but before this deadline is characterized by the fact that only a limited number of maneuvering options remain, while taking evasive action too early may violate the Rule 17 in COLREGs.

Furthermore, the stand-on ship is only permitted to take evasive action when there is evidence indicating that the give-way ship is not taking appropriate action according to the COLREGs. Only one work done by Cho et al. (2018) analyzes the ship action intention. The dynamic and uncertainty nature of ship action still needs more attention. It is therefore of great importance to conduct research on the give-way ship's action characteristics to quantitatively define what situation and stage is the stand-on ship in currently.

2.2. *Estimation of give-way ship's intention*

Even though intention estimation has attracted increasing attention in human-robot interaction (Omori et al., 2007; Fan et al., 2014) and road collision warning (Mochizuki and Ishikawa., 2015), only very little work focuses on the ship intention estimation in the maritime domain, see Table 1.

The maneuvering intent probability is calculated based on the intentional behavior and the dynamic Bayesian network, while the zero-mean Gaussian process noise is utilized to reflect the uncertainty of the kinematic and action models (Cho et al., 2018). This method also ignores the influence of the OS on the decision of the TS. The vessel intent and behavior is inferred for maritime security operations, such as countering piracy, in the work done by van den Broek et al. (2014). For other existing approaches analyzing ship conflict during the encounter process to detect near misses (Goerlandt et al., 2012a; Zhang et al., 2016a,b; Kim et al., 2017), hazardous encounter (van Iperen, 2012), and vessel conflicts (Wu et al., 2016), few of these attaches importance to the ship's action intention during the conflict process. Many existing approaches assume the ships involving in the encounter situation sail in a straight line with constant speed even though the conflict exists (Weng et al., 2012; Debnath and Chin, 2010), which is unrealistic (Du et al., 2019). Even though the work done by Mestl et al. (2016) used the hard maneuverings rate of turn (ROT) to reflect the encounter risk, ROT is currently not a reliable parameter due to the fact that ROT indicator is usually not connected to the AIS transponder, which has been discussed in (Mestl et al., 2016). Overall, the correctively understanding of other ship's intention needs more work, which contributes to reducing the ship collision caused by uncoordinated action.

2.3. Uncertainties of give-way ship's actions

Uncertainty is inherent to conflict analysis. The uncertainty of the give-way ship's action can be understood by recognizing that the give-way ship's action in the future is impossible to exactly describe due to a state of limited knowledge. Although many work have done to control the shio action (Zhu et al., 2018), there are many uncertainties of the give-way ship actions during the whole encounter process, which can affect the stand-on ship's judgment of the current traffic situation from her "first person" perspective, and therefore the uncertainties of give-way ship's action should be fully considered. However, most of the existing approaches in terms of conflict assessment did not consider the uncertainty, including objects' trajectory uncertainty and the environment disturbances (Sormunen et al., 2015; Park et al., 2016; Park and Kim, 2017). For instance, many researchers assume that the ship keeps her course and speed under the conflict threat, which ignores the dynamic nature of ship action, resulting into inaccurate conflict assessment (Chen et al., 2018; Huang et al., 2020b; Du et al., 2019).

There are three most frequently used methods for dealing with uncertainty in maritime domain: Bayesian probability theory modelled by probability (Hänninen, 2014), Dempster-Shafer theory of evidence by the degree of belief (Huang et al., 2014), and fuzzy set theory by the degree of set membership (Qu et al., 2011). Uncertainty in all the three approaches is quantified as a positive real number less than 1. However, there are many limitations and assumptions of each method. The Bayesian theory applies to situations where probabilities can meaningfully assigned. The Dempster-Shafer theory of evidence has strong links with probability theory while possibilities apply only to finite universal sets. Fuzzy sets approach uncertainty through notions of vagueness and impreciseness of human language, but their practical application in complex settings is limited as clear if-then rules need to be comprehensively enumerated, which often is not feasible.

Any simplified assumptions in the give-way ship's action could affect the conflict assessment so as to change the collision-avoidance decision drastically (Goerlandt et al., 2012b). According to the ship action definition, the ship action is closely related to ship maneuverability. Therefore, utilizing the reachable ship velocity to consider all the possible give-way ship's actions based on ship maneuverability is plausible to represent the uncertainty of ship action.

In brief, from the existing studies, it is found that work focusing on COLREGS-compliant elimination of conflict from the perspective of the stand-on ship is lacking, and that the applicability of existing research methods on this theme is limited by unrealistic assumptions; Estimation of give-way ship's intention from its actions has not been focused in the literature; the uncertainties of actions are significant but usually ignored for simplification.

3. Methodologies

Fig. 2 demonstrates a process of elimination of conflict, embedding the SLoD trigger. Firstly, the ship would receive all related information of the own ship (OS) and the target ships (TSs). Secondly, the OS would predict relevant trajectories in the future. Then, the OS assesses the conflict and finds that the TS has a real conflict with the OS. Incorporating the COLREGs, the OS would know its obligation:

- When the OS is the give-way ship, the OS needs to take evasive actions and FLoD is activated;
- When the OS is the stand-on ship, the OS needs to detect the SLoD stage and appraise the intention of the TS and action quality. Specifically, if the OS judges that the TS takes evasive actions sufficiently and in time, the OS has to remain her action, i.e. stay on course with the same speed. In this case, the FLoD works efficiently. If not, the OS has to trigger actions for passing safely according to the SLoD (the bold frame in Fig. 2).

The TS's intention estimation is to judge whether the ship is aware of the conflict and make the corresponding response. The conflict evolution analysis is to check whether TS's action is efficient to eliminate the conflict. The TS's intention estimation is the focus of this research, which is the first step for the activation of SLoD. Understanding the give-way ship's action and its intention during the encounter process intends to contribute to strengthening the stand-on ship's situational awareness.

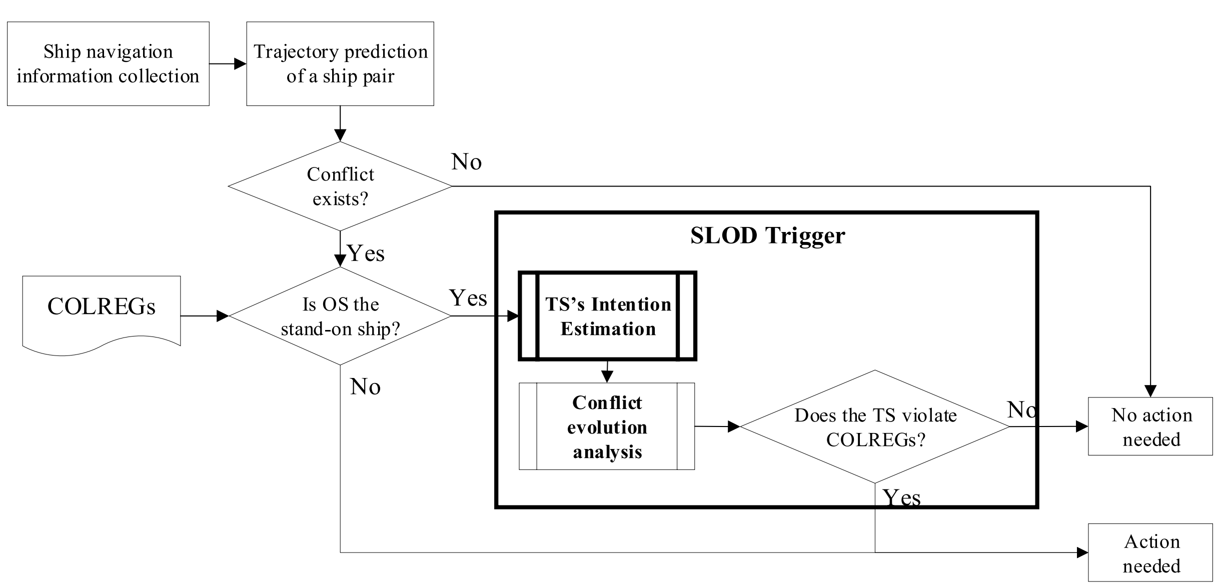

Fig. 2. Conceptual diagram of how the ship involved in conflict makes an action decision.

The definitions of ship's action and its intention are addressed in Section 1.2.

Understanding another ship's action intention is the precondition to make an effective evasive action decision, whereas the misunderstanding of another ship's action intention can cause uncoordinated actions and accidents. Hence, estimating the give-way ship's action intention is a possible way to improve the stand-on ship's situational awareness, which could contribute to reducing the ship collision caused by the uncoordinated actions. This is the foundation of the construction of the second protective layer 'SLoD'.

3.1. Explanation of key terminologies

Firstly, to quantitatively analyze the intention of the give-way ship during the encounter process, the ship action intention should be first clarified. According to the ship intention definition in Section 2.2, the intention of the give-way ship action during the encounter process is enumerated: normal navigation and evasive action for conflict elimination. Generally, the intention is considered to be elimination of conflict when the give-way ship changes her course or/and speed to avoid the ship conflict, while the ship intention is assigned as normal navigation if there is no conflict regardless the changes in her movements. Hence, the give-way ship action intentions can be distinguished by checking whether the conflict exists when the ship action changes. As the aim of this paper is to improve the situational awareness of the stand-on ship, the stand-on ship is set as own ship (OS) and the give-way ship is the target ship (TS).

Secondly, conflict can be measured as the overlap of two Ship Domains (SD) (Ulusçu et al., 2009; Wang, 2010; Weng and Xue, 2015). In this work, a circular SD is adopted for simplifying calculation, as in Weng et al. (2012). The overlap of the two circular ship domains is equivalent to one ship entering the circular-shape prohibit region around another ship, the radius of which is equal to the sum of the radii of the two ship domains.

3.2. Generic framework for intention estimation

Fig. 3 shows the framework of intention estimation of the give-way ship from the stand-on ship perspective. Three layers are presented. The first layer collects the all information/data needed for the following intention estimation, including ship trajectory, ship parameters and ship maneuverability, etc. As this research focuses on the ship intention estimation, how the ship trajectory is generated is simplified, with historical data being adopted to construct the ship trajectory.

The second layer is intention estimation model, containing four modules. The first module is the **Data Preprocessing module**. The traffic safety-related information of this ship pair is input in this module, including ship attributes and sailing-related information. Considering the COLREGS, the type of encounter scenario and the obligations of two ships are determined according to their relative course and relative position (Goerlandt et al., 2015). The "stand-on" ship is set as own ship, and its size (length L_{OS}) and trajectory $P_{OS}(x, y, t)$ are obtained. For the

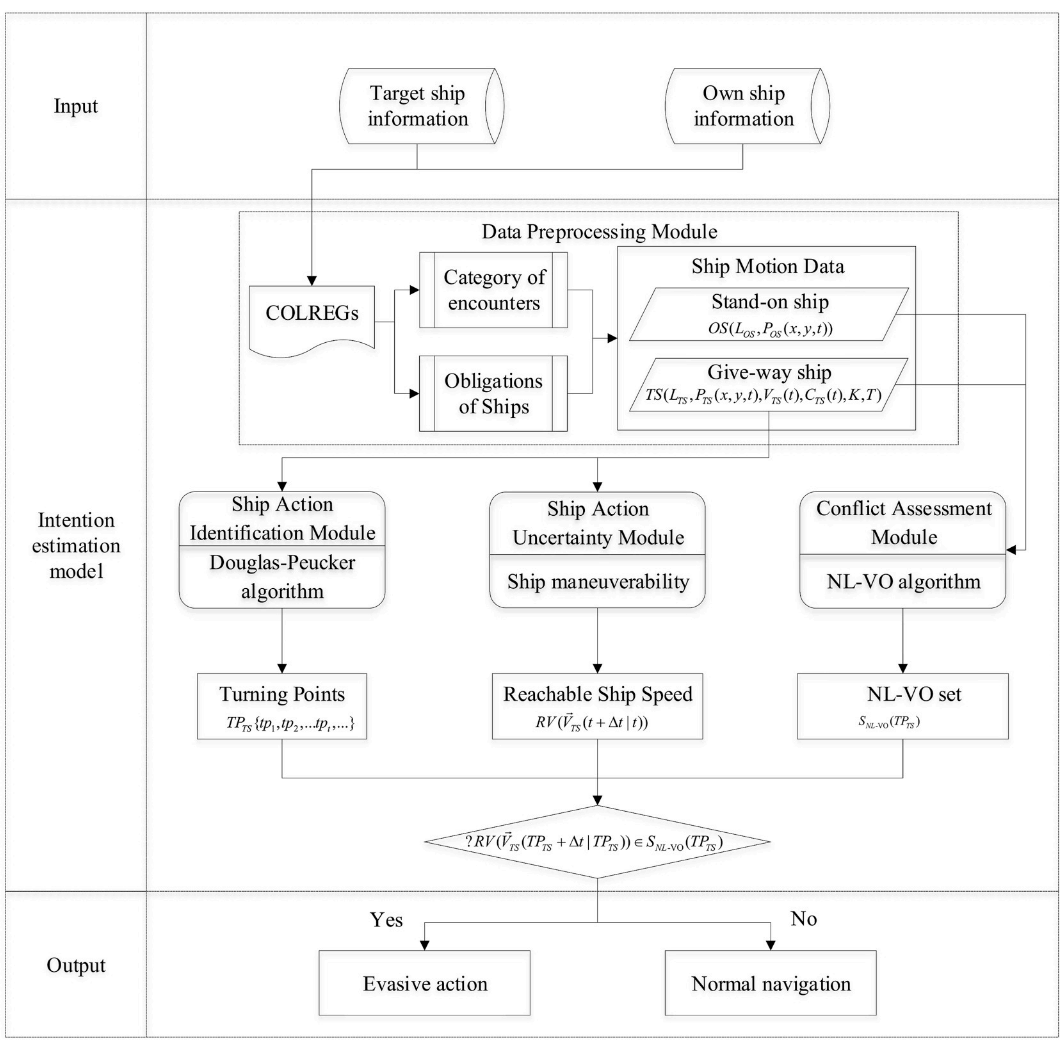

Fig. 3. Framework of give-way ship's intention estimation from stand-on ship perspective.

target ship, here is taken as the give-way ship, its size (length L_{TS}) and trajectory $P_{TS}(x,y,t)$, speed $\vec{V}_{TS}$ and course $\vec{C}_{TS}$, are set to be known. The give-way ship's turning ability index K and turning lag index T are obtained for the reachable velocity calculation to consider the uncertainty of give-way ship's action. The **Action Identification module** uses the Douglas-Peucker algorithm (D-P algorithm) to determine the turning points of the give-way ship $TP_{TS}\{tp_1, tp_2, \dots tp_t, \dots\}$, where tp denotes the time instance of each turning point, as elaborated in Section 3.3. Then, the **Action Uncertainty module** considers the uncertainty of the actions of the give-way ship which is bounded in a reachable velocity set $RV(\vec{V}_{TS}(t+\Delta t|t))$ based on the ship turning ability, as further explained in Section 3.4. The **Conflict Assessment module** employs the NL-VO algorithm to help the give-way ship to formulate a set of velocity $S_{NL-VO}(t)$ in TS's speed space leading to a conflict with the OS. The NL-VO algorithm is described in Section 3.5. Specifically, the conflict between OS and TS can be evaluated by assessing whether the reachable ship velocity of TS $RV(\vec{V}_{TS}(t+\Delta t|t))$ is in the conflicting course set $S_{NL-VO}(t)$.

The third layer judges the intention of the give-way ship via integrating all the information generated in the second layers. This information includes turning points of the give-way ship $TP_{TS}\{tp_1, tp_2, \dots tp_t, \dots\}$, reachable ship velocity at turning moment $RV(\vec{V}_{TS}(TP_{TS} + \Delta t|TP_{TS}))$, and the corresponding NL-VO set $S_{NL-VO}(TP_{TS})$. Finally, the ship action intention is quantitatively estimated by linking the ship action with the conflict to strengthen the OS's situational awareness.

3.3. Simplification method for ship trajectory based on Douglas-Peucker algorithm

The point of ship action change is distinct when the give-way ship takes significant action to eliminate conflict by setting the course change limit. However, the ship's heading may fluctuate slightly when the ship experiences a small course alteration under the effect of external conditions, such as wind, because of which it is not trivial to identify the ship action exactly.

The Douglas–Peucker (DP) algorithm (Douglas and Peucker, 1973) is considered one of the most accurate and effective methods to compress line data by reducing the number of positions of a trajectory while retaining only the important positions (Meratnia and Rolf, 2004; Muckell et al., 2010, 2014). It has been widely adopted in compression of ship trajectory data (Zhu et al., 2014; Zhang et al., 2016a,b; Mou et al., 2018; Zhao and Shi, 2018, 2019). Therefore, the D-P algorithm is utilized as the simplification method for ship trajectory to identify the ship action points. Its theory and schematic diagram are illustrated in Fig. 4. A straight line is connected between the two points at the beginning and the end of the ship trajectory, and the distances from the remaining points to this straight line are calculated. The maximum distance is compared with the compression threshold. The farthest point is retained if the distance exceeds the set compression threshold. Otherwise, all points between the ends of the straight line are discarded. The size of the compression threshold determines the availability of the compressed track. Therefore, the compression threshold is very important for trajectory compression, and this paper uses the restricted circular area to determine the compression threshold.

Concretely, the ship's trajectory consists of discrete points P1 to P11 in Fig. 4. In Fig. 4(a), the starting point P_1 and end point P_{11} of ship original ship trajectory are connected in a straight line as simplified ship trajectory (blue line), and the distance between the rest points P_2 to P_{10} and this simplified ship trajectory are calculated. P_7 is the farthest point and exceeds the compression threshold, so that P_7 (red dot) is the split point of this simplified ship trajectory. Hence, this ship trajectory is split into two sub-tracks at P_7 in Fig. 4(b). Then, these steps are repeated and new split points are obtained to determine the final simplified ship trajectory in Fig. 4(c), consisting of P_1, P_4, P_7, P_{10} and P_{11}, and more details can be seen in Zhao and Shi (2018). These discrete points of the

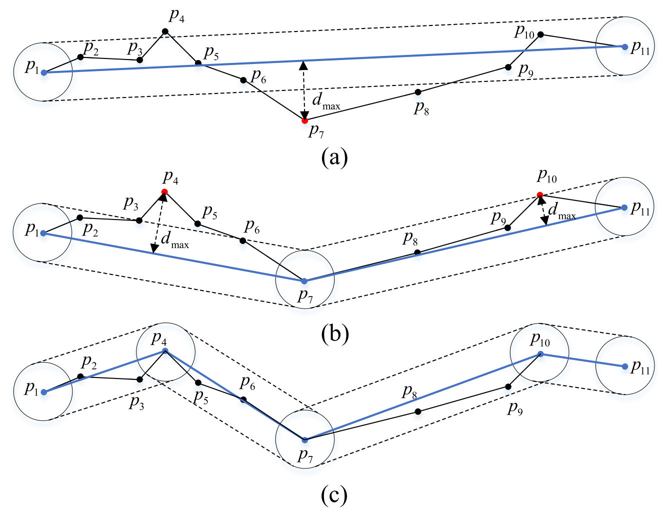

Fig. 4. Schematic diagram and the theory of the D-P algorithm, based on Douglas and Peucker (1973).

final simplified ship trajectory (P_1, P_4, P_7, P_{10} and P_{11}) can be regarded as the turning points $TP_{TS}\{tp_1, tp_4, tp_7, tp_{10}, tp_{11}\}$. The pseudo code for the D-P algorithm is described in Appendix.

3.4. Reachable velocity formulation

The give way ship's action uncertainties result in the uncertainty of its state in the next step. In principle, all possible give-way ship's actions should be considered in making the stand-on ship's conflict assessment. Except in exceptional circumstances, such as the ship out of control or situations where nobody is on watch in the bridge, etc., the give-way ships normally choose course alteration, speed change, or both to avoid a conflict. Statistical analysis shows that ships are more likely to alter course to avoid conflicts in actual operations (Baldauf et al., 2017). Therefore, this paper assumes that the give-way ship take course alteration for eliminating the encounter risk, while the magnitude of ship speed remains constant. This assumption is also widely used in maritime studies (Zhuo and Tang, 2008; Baldauf et al., 2017; Montewka et al., 2010; Zhang et al., 2012). The reachable ship velocity is utilized to consider all the possible give-way ship's actions, which depends on ship turning ability.

As shown in Fig. 5, the earth-fixed coordinate system OXY is adopted. The solid line with the arrow is the current ship speed $\vec{V}_{TS}(t)$. The current ship course $C_{TS}(t)$ is the angle at which the OX axis rotates anticlockwise to the direction of the ship speed $\vec{V}_{TS}(t)$. $u_{TS}(t)$, $v_{TS}(t)$ are the current ship speed $\vec{V}_{TS}(t)$ in the direction of OX and OY coordinate respectively. The magnitude of course change $\varphi(t+\Delta t|t)$ at each time step Δt depends on the ship turning ability, which determines the

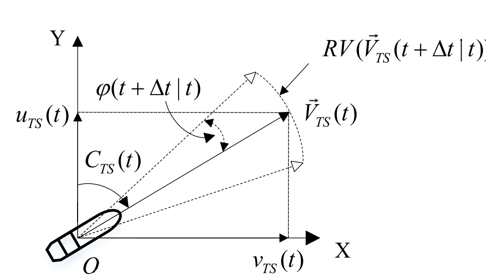

Fig. 5. The uncertainty of give-way ship action expressed by its reachable velocity.

reachable ship speed $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ in the next step, marked as dotted arc. The reachable ship speed $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ contains current ship speed $\overrightarrow{V}_{TS}(t)$.

Two kinds of hydrodynamic models, namely Abkowitz model (Zhang and Zou, 2011) and Maneuvering Modeling Group (MMG) model (Tao et al., 2019), are commonly used to describe ship maneuverability. However, determining the parameters of these models is a challenging work. Thus, Nomoto model (Nomoto et al., 1956), a simplification of MMG model only requires limited inputted parameters, is popular in various studies (Carrillo and Contreras, 2018; Banazadeh and Ghorbani, 2013; Nomoto et al., 1956; Fossen, 2011; Ren et al., 2018). The research of estimating parameters of Nomoto model could be found in (Journee, 1970; Perera et al., 2011; Banazadeh and Ghorbani, 2013), which is feasible in practice. Therefore, the Nomoto model is chosen in this work to model her turning ability to obtain the reachable ship velocity, as it is considered sufficiently effective and comparatively simple:

$$\mathrm{T}\dot{r}+r=\mathrm{K}\delta, \tag{1}$$

where r is the yaw rate (rad/s) and $\dot{r}$ is the acceleration of yaw rate. δ is demanded rudder angle, and $-35^\circ \le \delta \le 35^\circ$.

Based on the assumption that there is no deviation between the ship course and her heading, the change of ship course at each time step Δt based on her turning ability can be calculated:

$$\psi(t+\Delta t|t)=\int_t^{t+\Delta t} r dt = K\delta\left(t-T+T\cdot e^{-t/T}\right). \tag{2}$$

Hence, ignoring the speed loss during the steering process, the reachable ship velocity $RV(\overrightarrow{V}(t+\Delta t|t))$ can be obtained:

$$\begin{aligned} RV(\overrightarrow{V}_{TS}(t+\Delta t|t)) &= \begin{pmatrix} u_{TS}(t+\Delta t|t) \\ v_{TS}(t+\Delta t|t)\end{pmatrix} = V_{TS}\begin{pmatrix}\cos(C_{TS}(t+\Delta t|t)) \\ \sin(C_{TS}(t+\Delta t|t))\end{pmatrix} \\ &= V_{TS}\begin{pmatrix}\cos(C_{TS}(t)+\psi(t+\Delta t|t)) \\ \sin(C_{TS}(t)+\psi(t+\Delta t|t))\end{pmatrix}, \end{aligned} \tag{3}$$

where V_{TS} is the magnitude of ship speed $\overrightarrow{V}_{TS}(t)$.

3.5. Non-linear velocity obstacles algorithm structure

To measure the conflict from the ship action perspective, the velocity obstacle (VO) technique is utilized. The idea of VO is to project the spatiotemporal relationship between a ship pair involved into encounter situation (relative distance, speed, course, etc.) into one ship's velocity domain, based on which the conflict can be judged by checking whether the velocity of the ship falls into this velocity obstacle zone (Huang et al., 2018; Chen et al., 2018). The ship's velocity falling into this velocity obstacle zone is the conflicting velocity that might lead to a conflict. Considering that it is unrealistic to assume the ship to be sailing in straight with constant speed, the NL-VO algorithm is utilized as a basis to analyze the conflict at different encounter stage. The NL-VO algorithm is proposed by Large et al. (2002), with its first application in the maritime domain by Huang and van Gelder (2017). The highlight of NL-VO algorithm is that the target ship does not need to be assumed to sail in a straight line at the constant speed during the whole encounter process, if the trajectory of target ship is known, as discussed also in Du et al. (2019). The NL-VO algorithm has subsequently been applied for ship collision prevention (Huang et al., 2018, 2019; Huang and van Gelder, 2019), and collision candidate detection (Chen et al., 2018). However, the contributions of their works mainly focus on introducing NL-VO algorithms in waterway safety management and ship collision avoidance without considering the obligation of ships compliant with COLREGs. Our work expands the applications of NL-VO algorithms on preventing accidents to quantify COLREGs for the stand-on ship.

The NL-VO set is the collection of all the conflicting velocities leading to the ship conflict. The basic idea of NL-VO algorithm is to identify a NL-VO set. This NL-VO set can be formulated as follows:

$$\begin{cases} S_{NL\_VO}(t_0)=\bigcup_{t}^{\infty}\left(\dfrac{P_{OS}(x,y,t)-P_{TS}(x,y,t_0)}{(t-t_0)}\right)\oplus\dfrac{ConfP(O,R)}{(t-t_0)}, \\ ConfP(O,R)=\{\|P_{OS}(x,y,t)-P_{TS}(x,y,t_0)\|\le R\} \end{cases} \tag{4}$$

where $S_{NL\_VO}(t_0)$ is the NL-VO set at current moment t_0. $P_{OS}(x,y,t)$ is the ship trajectory of the OS after t_0, while $P_{TS}(x,y,t_0)$ is the current TS's position. $ConfP$ is the term describing all the possible positions of the TS when ship conflict occurs between the OS and the TS at time t_0. $\oplus$is Minkowski addition, and the prohibited region around the OS can be formulated as $P_{OS}\oplus ConfP(O,R)$. R is the radius of circular-shape prohibit region around the OS, according to the conflict definition, which is equal to the sum of two ship domain's radius. The ship domain is set as three times of the ship length, as in Weng et al. (2012). If the reachable speed vector of the give-way ship $RV(\overrightarrow{V}_{TS}(t_0+\Delta t|t_0))$is the element of $S_{NL\_VO}(t_0)$, the ship conflict exists. The formula derivation process is elaborated in (Huang et al., 2018).

3.6. Conflict analysis during the encounter process

3.6.1. Encounter process analysis

From the TS perspective, when the ship pair is approaching, the encounter process can be roughly divided into the following stages (Fig. 6) according to the different ship action intentions: (1) non-conflict stage, and (2) conflict stage. Notably, no ship action during the (1) non-risk encounter stage is regarded as evasive action because the intention for evasive action is to eliminate the accident risk. Hence, the evasive action stage ranging from starting point (t_{as}) to ending point (t_{ae}) is a subset of (2) conflict stage. There is a recovery phase in which the ship returns to its original course or planned trajectory during this encounter process. This recovery phase belongs to the evasive action stage if this recovery phase happens when the ship is under conflict threat and vice versa. Therefore, evasive action occurs point (t_{as}) is when the ship starts to take action responding to the accident risk, while evasive action ends point (t_{ae}) presents that there is no operation is in the subsequent encounter process before the conflict passing. As shown in Fig. 6, the black triangle on the TS's trajectory is the ship action change for the normal navigation as there is no conflict when the ship action changes, while the solid black circle on the TS's trajectory is the ship evasive action. The hollow black circles on the TS's trajectory represent the starting and ending points of conflict stage.

As the ship takes different ship actions in the different encounter stages, these stages are quantitatively explained combined with the NL-VO velocities set and ship turning ability. In the non-risk encounter stage (1), there is no conflict as the intersection between TS's reachable velocity $RV(\overrightarrow{V}_{TS}(t_0+\Delta t|t_0))$ and NL-VO velocities set $S_{NL\_VO}(t_0)$ is empty. In the conflict stage (2), the give-way ship's reachable velocity $RV(\overrightarrow{V}_{TS}(t_0+\Delta t|t_0))$ and the NL-VO velocities set $S_{NL\_VO}(t_0)$ have non-empty intersections. This means that a conflict exists due to the dynamic and uncertain nature of ship actions in the complex maritime traffic environment. Consequently, the intention of the give-way ship's action can be determined by judging whether its reachable velocity at turning points $RV(\overrightarrow{V}_{TS}(TP_{TS}+\Delta t|TP_{TS}))$ has a non-empty intersection with the corresponding NL-VO velocities set $S_{NL\_VO}(TP_{TS})$.

3.6.2. Ship action intention identification model

The ship action intention is related to the conflict. The conflict between a ship pair exists when the TS's reachable velocity $RV(\overrightarrow{V}_{TS}(t_r+\Delta t|t_r))$ and the NL-VO velocities set $S_{NL\_VO}(t_r)$ in TS's speed space are overlapping, which is formulated as follows.

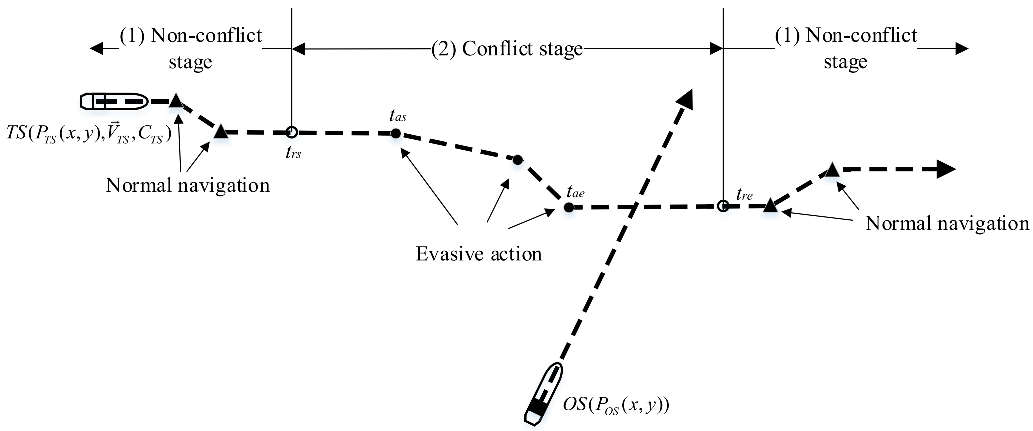

Fig. 6. Ship encounter process from the TS perspective (crossing encounter as example). Note: evasive action refers to the maneuvers taken by one ship to avoid conflict, while the other maneuvers are considered to be normal navigation, e.g. turning at waypoints, adapting its course.

$$\begin{cases} RV(\overrightarrow{V}_{TS}(t_r+\Delta t|t_r))\cap S_{NL\_VO}(t_r)\neq\varnothing \\ t_{rs}=\min(t_r) \\ t_{re}=\max(t_r) \end{cases}, \quad (5)$$

where $RV(\overrightarrow{V}_{TS}(t_r+\Delta t|t_r))$ is the reachable velocity of the TS and the $S_{NL\_VO}(t_r)$ is the NL-VO set in the TS's speed space at time t_r. t_r is the time that conflict exists. t_{rs} and $t_{re}$are the starting moment and ending moment of conflict stage respectively.

After using the D-P algorithm to simplify the ship trajectory as explained in Section 3.3, the ship trajectory is a fold line connecting the turning points $TP_{TS}\{tp_1,tp_2,...tp_t,...\}$. The turning points are where the ship takes actions, i.e., altering course as in this paper speed changes are not considered. The intention of all these turning points is analyzed by checking whether there is a conflict when the ship is at turning points, taking the ship action uncertainty into consideration. Therefore, if the intersection between the give-way ship's reachable velocity $RV(\overrightarrow{V}_{TS}(TP_{TS}+\Delta t|TP_{TS}))$ and the NL-VO set $S_{NL-\mathrm{VO}}(TP_{TS})$ in TS's speed space is not empty, this ship action in this turning point corresponds to an evasive action. The corresponding calculation formula for identifying evasive action is as follows:

$$\begin{cases} RV(\overrightarrow{V}_{TS}(t_a+\Delta t|t_a))\cap S_{NL-\mathrm{VO}}(t_a)\neq\varnothing, t_a\in TP_{TS}\{tp_1,tp_2,...tp_t,...\} \\ t_{as}=\min(t_a) \\ t_{ae}=\max(t_a) \end{cases}, \quad (6)$$

where $RV(\overrightarrow{V}_{TS}(t_a+\Delta t|t_a))$ is the reachable velocity of TS at next moment based on the ship state and her action at each evasive action time t_a that belongs to $TP_{TS}\{tp_1,tp_2,...tp_t,...\}$. The starting point ($t_{as}$) and ends point ($t_{ae}$) of evasive action are the minimum and maximum value of the each evasive action time t_a. Clearly, the $[t_{as},t_{ae}]\subseteq[t_{rs},t_{re}]$. Accordingly, those ship action changes for the navigation purpose if the give-way ship's reachable velocity $RV(\overrightarrow{V}_{TS}(TP_{TS}+\Delta t|TP_{TS}))$ at the turning points is not an element of NL-VO set $S_{NL-\mathrm{VO}}(t_a)$, which is the normal navigation, marked as a black triangle in Fig. 6.

4. Case study

Two types of cases are studied to demonstrate and check the performance of the proposed method. One is the two-ship case based on the designed simulations in Section 4.1 including crossing and overtaking encounter. Another one is a multi-vessel case based on AIS data in North Atlantic, which is presented in Section 4.2. These case studies focus on model testing and model results analysis.

These scenarios were created based on Rule11 to 18 in COLREGs and certain assumptions:

1. All the encounter scenarios represent in good visibility conditions so that officers onboard each ship involved in the encounter can see the other ship (Rule 11).
2. For two power-driven vessels underway, the vessel which has the other on her own starboard side is the give-way ship in crossing encounter (Rule 15), and the vessel overtaking any other is the give-way ship (Rule 13). However, no ship can be regarded as the stand-on ship in the head-on encounter (Rule 14).
3. The multi-vessel encounter is divided into multiple two-ship encounters. Because Rule 11 in the COLREGs, rules in this section apply to vessels in sight of one another.
4. A power-driven vessel underway shall keep out of the way of a vessel engaged in fishing (Rule 18).
5. The stand-on ship is set as OS and the give-way ship is the TS as our work aims to support navigator on the stand-on ship to perform her obligation by estimating the give-way ship's action intention.

4.1. Two-ship encounter based on simulations

4.1.1. Scenarios design

As the scope of this research aims to improve stand-on ship's situational awareness to eliminate the conflict, two typical encounter scenarios are designed to demonstrate the model's rationale, which can be seen in Table 2.

The precondition of using the NL-VO algorithm to evaluate the conflict between a ship pair is that the trajectory of the TS (give-way ship) is known in advance. As the focus of this research is improving OS's situational awareness by estimating TS's intention, the trajectory and the related static and dynamic parameters of a ship pair are set as known in advance (Table 2). The initial position of the OS IP_{TS} is set at the origin (Fig. 7) and that of TS are given in Table 2. In Table 2, TR_{TS} and TR_{OS} are the designed turning points of TS and OS respectively. Both the ship speed of TS V_{TS} and OS V_{OS} are measured relative to the ground.

In Fig. 7, the solid and dotted line are the trajectory of TS and OS respectively. The designed turning points of TS are marked as diamond on the trajectory of TS. The time step of conflict analysis using NL-VO algorithm is 10 s for simplifying calculation, and that of turning points identification using D-P algorithm is 1s to avoid missing turning points. The radius of the restricted circular area to determine the compression threshold is set as 15m. The simulation time is 800s for ship intention estimation and 900s for the generation of ship trajectory. Each ship is 200 m in length, and the radius of the circular ship domain is set as three times of the ship length, as in Weng et al. (2012). The K and T of give-way ship are set as $2V_{TS}/L_{TS}$ and $2L_{TS}/V_{TS}$ respectively in this paper (Hong and Yang, 2000).

Table 2
The settings of two encounter scenario with designed turning points.

Encounter Scenarios		TS				OS		
		$IP_{TS}:m$	$V_{TS}:m/s$	TR_{TS}		$V_{OS}:m/s$	TR_{OS}	
				$t:s$	$C_{TS}:^{\circ}$		$t:s$	$C_{OS}:^{\circ}$
Scenario 1.1	Overtaking Encounter	(-1000, 0)	6	1–60 61–150 151–240 241–420 421–570 571–900	0 10 30 0 −20 0	4	1–60 61–300 301–450 451–600 601–900	0 −10 0 10 0
Scenario 1.2	Crossing Encounter	(-2000, −2000)	5	1–180 181–240 241–360 361–540 541–720 721–900	90 60 45 90 110 90	5	1–900	180

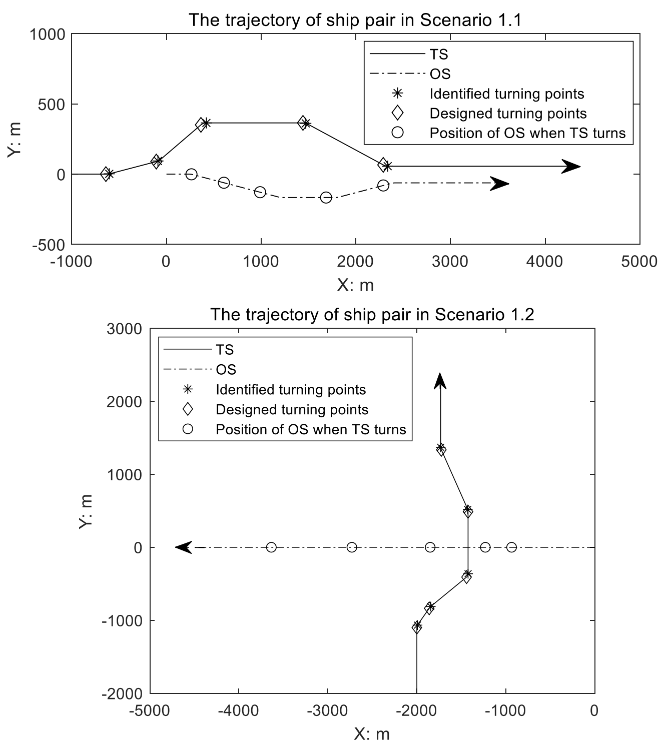

Fig. 7. Designed two typical encounter scenarios for demonstrating the model rationale (Note: for detailed parameters see Table 2).

4.1.2. Results of ship action intention analysis

The result of conflict analysis and identified turning points is presented in Table 3, and the identified turning points $TP_{TS}\{tp_1, tp_2, ...tp_t, ...\}$ are marked as the black star on the trajectory of TS as shown in Fig. 7. The black circle on OS's trajectory are the OS's position when the TS takes action. From Fig. 7, the identified turning points in Table 3 are consistent with the designed turning points in Table 2, which illustrates that this proposed method can accurately identify the ship action and the conflict.

Table 3
The result of conflict analysis and identified turning points by the proposed methods.

Encounter Scenarios	$t_r:s$	$TP_{TS}:s$				
Overtaking	1–791	67	154	251	426	579
Crossing	1–401	188	247	371	547	728

Note: t_r is the time that conflict exists, TP_{TS} is the moment when the give-way ship is in the turning points.

The visualization of the TS intention estimation results in Scenario 1.1 and Scenario 1.2 are illustrated in Fig. 8 and Fig. 9 respectively. The current speed of the give-way ship $\vec{V}_{TS}$ is marked as the red star and its reachable ship velocity $RV(\vec{V}_{TS}(t+\Delta t|t))$is the blue arc. The black circle is the NL-VO set $S_{NL-\mathrm{VO}}(t)$ in TS's speed space at different moments. If $RV(\vec{V}_{TS}(t+\Delta t|t))$ has non-empty intersection with $S_{NL-\mathrm{VO}}(t)$, there is a conflict. The larger the radius of the black circle, the potential danger is more urgent in the temporal scales. More specifically, if the $\vec{V}_{TS}$ and/or $RV(\vec{V}_{TS}(t+\Delta t|t))$ falls into the bigger $S_{NL-\mathrm{VO}}(t)$, the conflict will occur earlier. Further, the closer the TS's velocity is to the center of the black circle, the potential danger is higher in the spatial scales, which means there is less distance to the closest point of approach (DCPA) value at corresponding time moment.

Fig. 8 illustrates the results of the TS intention estimation in Scenario 1.1. For the overtaking encounter, the conflict exists during the whole encounter process, see the conflict stage in Fig. 8. There are five turning points identified by using the D-P algorithm, as shown in Table 3. The TS turns to port 10° at 67s and 20° at 154s to stay away from the OS, which are labelled as evasive action as these ship action happened inside the conflict stage (Fig. 8(a) and (b)). At time 251s, the TS turns to starboard to return to its original course 0°. To return its original planned route, the TS turns to starboard 20° at 426s and then returns to 0° at 579s. As this recovery process happens before the conflict is wholly disappeared, both $\vec{V}_{TS}$ and $RV(\vec{V}_{TS}(t+\Delta t|t))$ fall into the NL-VO set $S_{NL-\mathrm{VO}}(t)$, and therefore all the rest three ship actions happens at 251s, 426s and 579s are also evasive action for elimination of conflict (Fig. 8(c), (d) and (e)). Based on these analysis, the TS's evasive action is not efficient enough that the conflict still exists after TS's action, and therefore the OS in the stand-on position may needs to act.

Fig. 9 illustrates the results of the TS intention estimation in Scenario 1.2. For the crossing encounter, the conflict stage starts from 1s to 401s, see the conflict stage in Fig. 9. From Table 3, it is seen that the TS takes five actions at 188s, 247s, 371s, 547s and 728s. Since the first three actions are taken when there is conflict, these first three actions are the evasive actions. In Fig. 9(a), 9(b) and 9(c), the $RV(\vec{V}_{TS}(t+\Delta t|t))$ has the non-empty intersection with $S_{NL-\mathrm{VO}}(t)$. However, the intention of last two ship actions happens in 547s and 728s are normal navigation. In Fig. 9(d), neither $\vec{V}_{TS}$ nor $RV(\vec{V}_{TS}(t+\Delta t|t))$ falls into $S_{NL-\mathrm{VO}}(t)$, so no conflict exists between this ship pair now. In Fig. 9(e), the NL-VO set is an empty set so that there is no non-empty intersection between $RV(\vec{V}_{TS}(t+\Delta t|t))$ and $S_{NL-\mathrm{VO}}(t)$. The TS alters courses at 547s (from 90° to 110°) and 728s (from 110° to 90°) to return to its original route, and there is no conflict existing. Therefore its corresponding intentions are

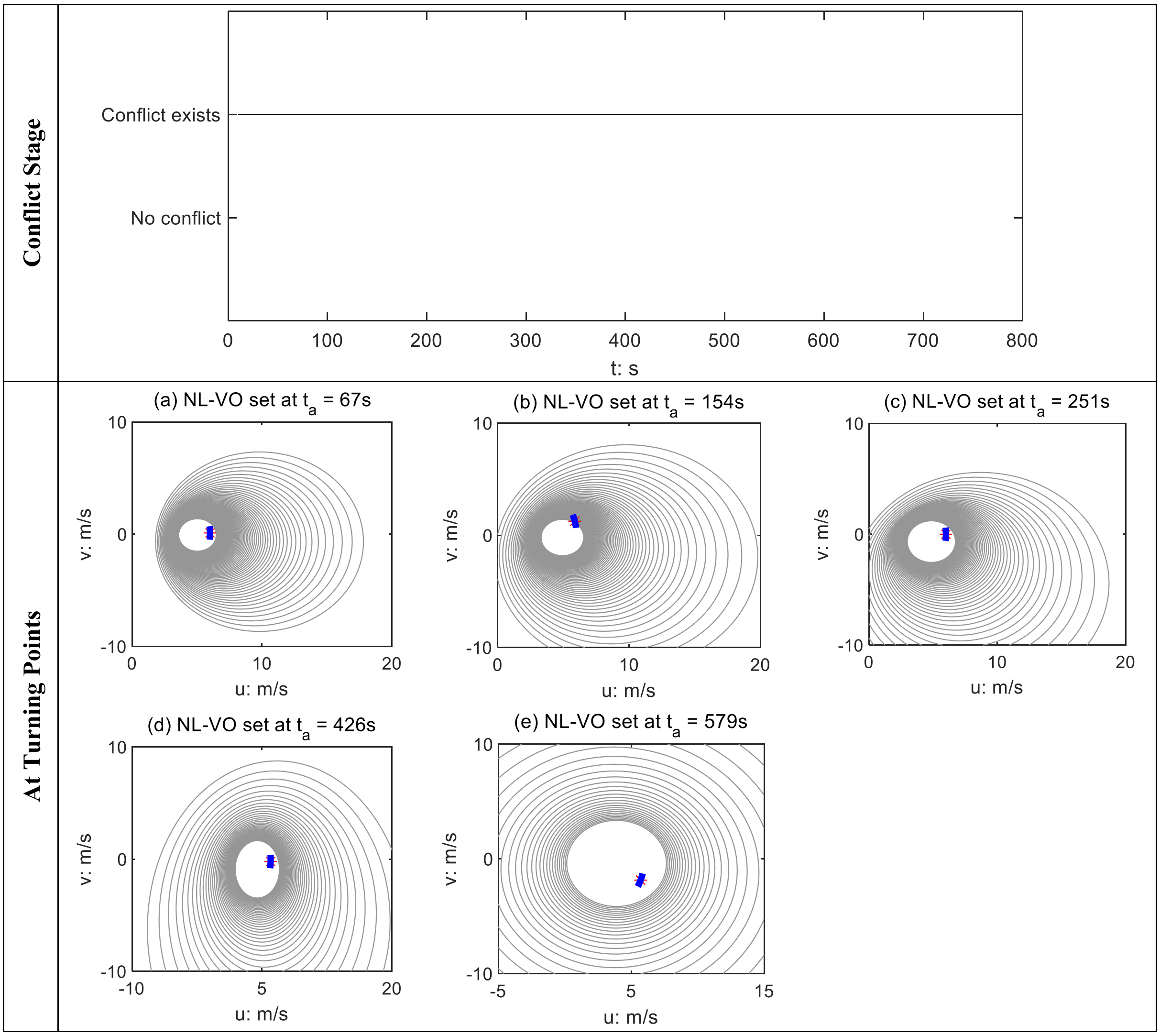

Fig. 8. Conflict detection and ship intention estimation during different encounter stages in overtaking encounter scenario.

accurately identified as normal navigation. As the TS's action can efficiently eliminate the conflict, the OS in the stand-on ship should remain her course and speed unchanged according to COLREGs.

4.2. Multi-vessel encounter based on historical AIS data

As shown in Fig. 10, there was a multi-vessel encounter between Ship1 (smaller oil tanker with 96m in length), Ship2 (fishing vessel with 23m in length) and Ship3 (bigger oil ship with 171m in length). The discrete points are the historical trajectories of these three ships in real AIS data after processing (such as data cleaning and filtering) and the lines are the ship trajectories after linear interpolation based on AIS data. Different colors represent different ships. Particularly, the blue color is Ship1. The red and black colors are Ship2 and Ship3 respectively.

According to Rule 18 in COLREGs, the two power-driven oil tankers Ship1 and Ship3 shall keep out of the way of the fishing vessel Ship2. Therefore, Ship2 is in the stand-on position when encountering Ship1 and Ship3. There is a crossing encounter between Ship1 and Ship 3, and the Ship 3 is the stand-on ship as she is in the starboard of Ship1 according to Rule 15 in COLREGs.

4.2.1. Results of conflict detection and ship action identification

When the compression threshold is set as 15m, the results of conflict analysis and identified turning points of TS based on the proposed method are listed in Table 4.

For the encounter between Ship1 and Ship2, the Ship1 is the give-way ship as the Ship2 is the fishing vessel. Taking Ship1 as the TS, a conflict exists in two periods: from 631s to 721s and from 871s to 921s. There are twenty-three turning points of Ship1 in the give-way position.

For the crossing encounter between Ship1 and Ship3, the TS is the Ship1 in the give-way position, and the conflict appeared from the beginning to 641s and from 911s to 981s. Twenty-three turning points of Ship1 are identified.

There is a crossing encounter between Ship2 and Ship3. The give-way ship is Ship3. Thus, Ship3 is set as TS. Except for the period from 252s to 330s, a conflict exists from the beginning to 1461s. There are 14 turning points of Ship3. More details can be seen in Table 4.

4.2.2. Visualization of ship intention estimation

Fig. 11 shows the location of the identified ship action points and the result of the intention estimation of these turning actions. The lines with different colors are the trajectories of the different interacting ships. The points on a ship trajectory are the identified turning points of this ship. The points on the trajectory of Ship1 marked as red circles represent the evasive actions of Ship1 aiming to avoid a collision with Ship2. The points on trajectory of Ship1 marked as black squares represent the evasive actions of Ship1 aiming to avoid a collision with Ship3. The

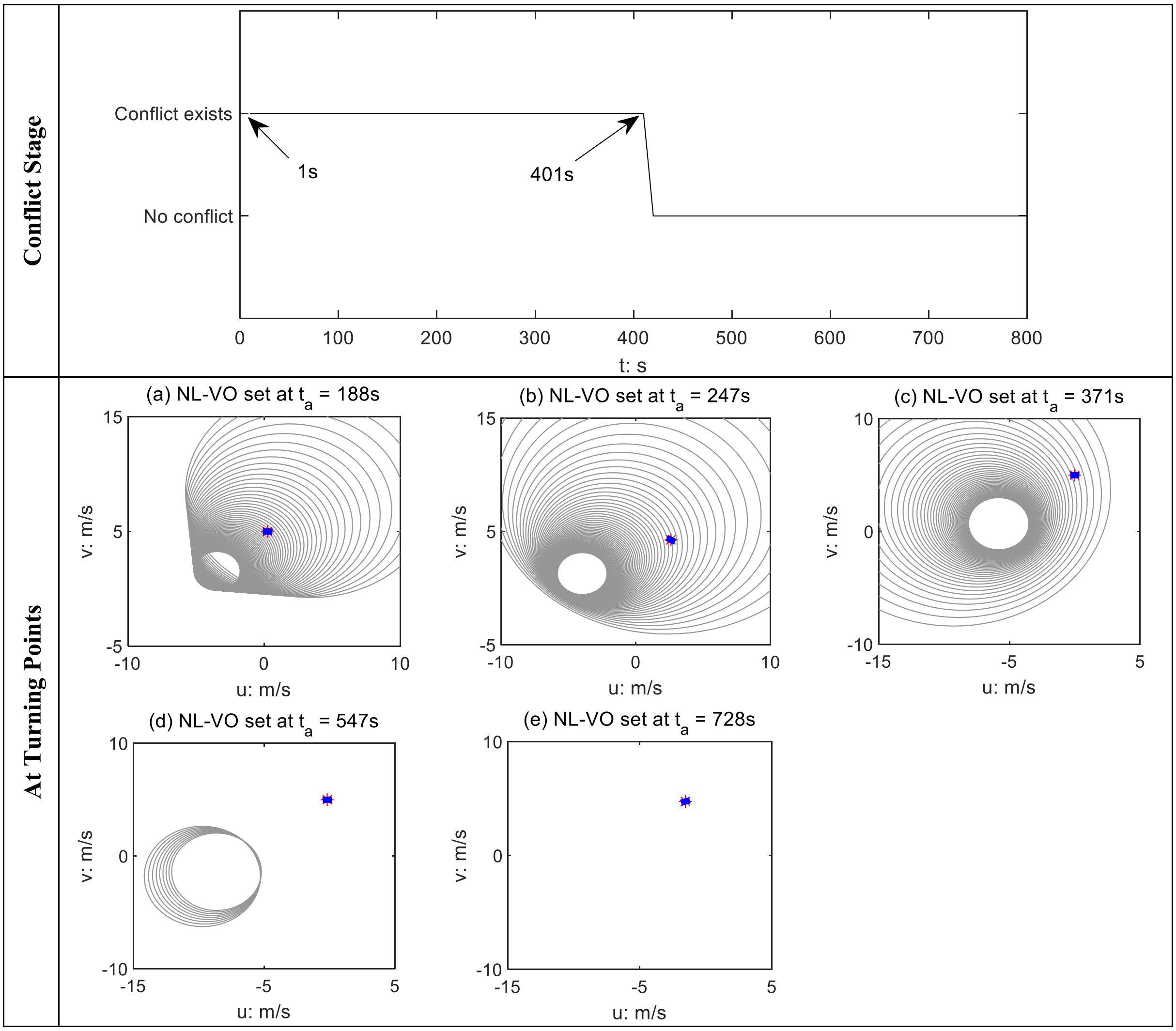

Fig. 9. Conflict detection and ship intention estimation during different encounter stages in crossing encounter scenario.

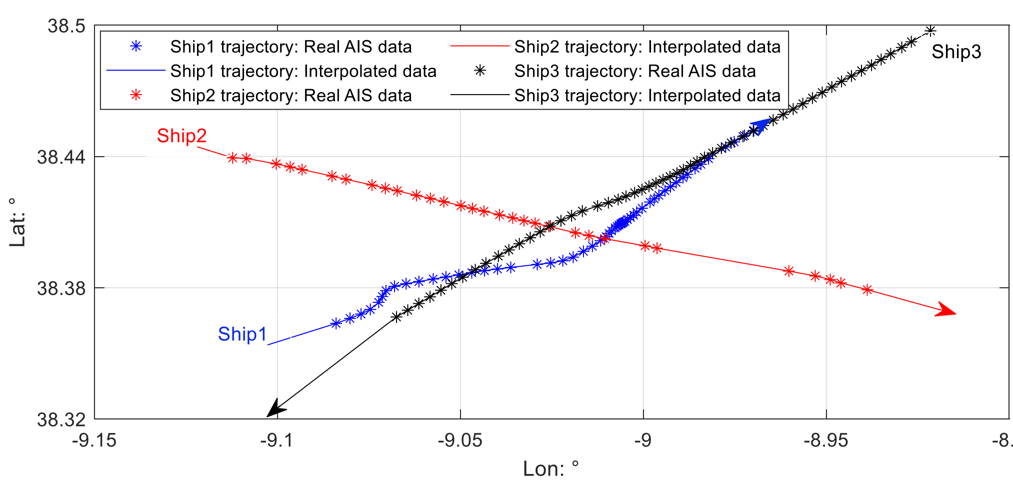

Fig. 10. The ship trajectories in a multi-vessel encounter scenario.

points on the trajectory of Ship3 marked as red diamonds represent the evasive actions of Ship3 aiming to avoid a collision with Ship2. The intention of the remaining turning points are estimated as the normal navigation. The process of intention estimation is elaborated in Figs. 12–14.

For the crossing encounter between Ship1 (TS) and Ship2 (OS), the

Table 4
The result of conflict analysis and give-way ship's action identification in multi-vessel encounter scenario.

Encounter Scenarios	t_r : s	TP_{TS} : s
Ship1 – Ship2	631-721, 871-921	434, 574, 634, 711, 831, 891, 951, 1320, 1621, 1681, 1741, 1870, 1931, 1991, 2111, 2351, 2661, 2841, 2901, 3169, 3820, 3950, 4141
Ship1 – Ship3	1-641, 911-981	434, 574, 634, 711, 831, 891, 951, 1320, 1621, 1681, 1741, 1870, 1931, 1991, 2111, 2351, 2661, 2841, 2901, 3169, 3820, 3950, 4141
Ship2 – Ship3	1-251, 331-1461	381, 561, 862, 1412, 1661, 1963, 2091, 2151, 2352, 2412, 2532, 2713, 2901, 3391

conflict detection result can be seen from the first figure in Fig. 12. The conflict exists at two periods, ranging from 631s to 721s, and from 871s to 921s. There is no conflict at the initial encounter stage before 631s as neither the $\overrightarrow{V}_{TS}$ and $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ during this period falls into the NL-VO set $S_{NL-\mathrm{VO}}(t)$. According to the result of ship action identification listed in Table 4, Ship1 turned to port at 434s and 574s (Fig. 12(a)) when there is no conflict between this ship pair so these two ship actions are for normal navigation. A conflict occurs from 631s onwards. Ship1 turned to port at 634s aiming to pass Ship2 by Ship2's stern. Due to Ship1's efficient evasive action at 634s and 711s when Ship1's reachable speed $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ has non-empty intersection with the NL-VO set $S_{NL-\mathrm{VO}}(t)$ (Fig. 12 (b)(c)), there is no conflict between this ship pair from 721s to 871s. Even though Ship1 turned to starboard aiming to pass the Ship2 by Ship2's bow at 831s, this is regarded as normal navigation as no conflict exists (Fig. 12(d)). The conflict occurs again from 871s onwards. When the Ship1 turns to starboard at 891s, there is a conflict because both the $\overrightarrow{V}_{TS}$ and $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ falls into the NL-VO set $S_{NL-\mathrm{VO}}(t)$, and therefore this turn is for conflict elimination (Fig. 12(e)). After 921s, there is no conflict between Ship1 and Ship2, so all the remaining turning after 921 are for normal navigation (Fig. 12(f)).

Fig. 13 illustrates the results of the Ship1 (TS) intention estimation for the crossing encounter between Ship1 and Ship3. In the first period of conflict occurring from the beginning to 641s, the intention of these three action performed within this period, including action at 434s, 574s and 634s, are estimated as conflict elimination, see Fig. 13(a)(b)(c). At 434s and 634s, only the reachable ship speed of Ship1$RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ is inside the NL-VO set $S_{NL-\mathrm{VO}}(t)$. At 574s, both the $\overrightarrow{V}_{TS}$ and $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ during this moment fall into the NL-VO set $S_{NL-\mathrm{VO}}(t)$. There is no conflict between this ship pair between 641s and 911s, so the ship turnings which occurred at 711s, 831s and 891s are interpreted as normal navigation, see Fig. 13(d)(e)(f). As Ship 1 keeps turning to starboard, the conflict re-occurs between 911s and 981s, see the conflict stage in Fig. 13. With the efficient evasive action performed at 951s (Fig. 13(g)), there is no conflict afterwards. For example, the ship turning at 1320s is judged as normal navigation (Fig. 13(h)).

Fig. 14 illustrates the results of the Ship3 (TS) intention estimation for the crossing encounter between Ship2 and Ship3. The conflict stage of Fig. 14 illustrates the result of conflict detection. In the first period of conflict, from the beginning to 251s, no turning points are detected. The first turning point of Ship3 is detected at 381s, which is within the second period of conflict existing stage. As seen in Fig. 14(a), the Ship3's reachable speed $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ falls into the NL-VO set $S_{NL-\mathrm{VO}}(t)$, so this turn is evasive action. Before 1461s when the conflict exists, there are three ship turning points. From Fig. 14(b)(c)(d), both the $\overrightarrow{V}_{TS}$ and $RV(\overrightarrow{V}_{TS}(t+\Delta t|t))$ of Ship3 at these moments fall into the NL-VO set $S_{NL-\mathrm{VO}}(t)$, so these three ship turnings are regarded as evasive actions for conflict elimination. As the TS's efficient evasive action, the conflict has been efficiently eliminated after 1461s. Therefore, all the ship turns which happened after 1461s, such as 1661s (Fig. 14(e)) and 1963s (Fig. 14(f)) are for normal navigation.

5. Discussion

5.1. Advantages and relevant applications of the proposed method

The proposed method aims at improving the OS's situational awareness by analyzing the TS's action and its intention. In the case study, the proposed method can identify the motivation behind the TS's actions. In particular, it can distinguish the ship action for normal navigation purposes or for conflict elimination purposes. Nonetheless, more tests are needed to confirm the plausibility of this proposed method.

Traditionally, the intention estimation of the TS relies on the information/data from the TS, while those methods ignore the influence of the OS on the decision of the TS. In this article, the intention of the TS is estimated by comparing the TS's action and the conflict in a pairwise ship encounter. The precondition of the OS using the NL-VO algorithm to evaluate the conflict between a ship pair is that the trajectory of OS is known in advance so that the OS's impact on the TS's intention is taken into consideration, which makes the conflict assessment more accurate and realistic. Compared with the most commonly used method based on CPA (Closest Point of Approach) and TCPA (Time to CPA), both the dynamic and uncertain nature of ship action are considered in the present approach, instead of making a hypothesis of straight navigation at a

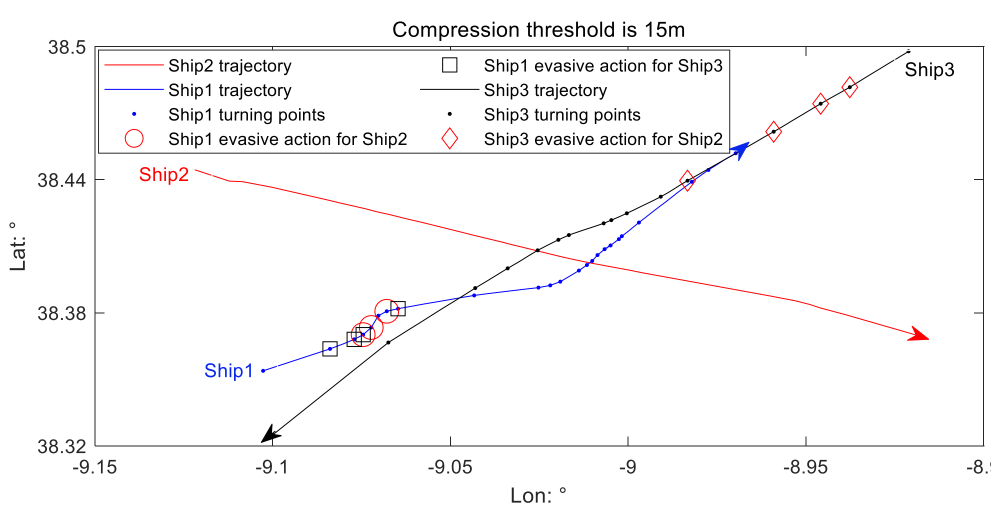

Fig. 11. The visualization of ship intention estimation when compression threshold is 15m in multi-vessel encounter scenario.

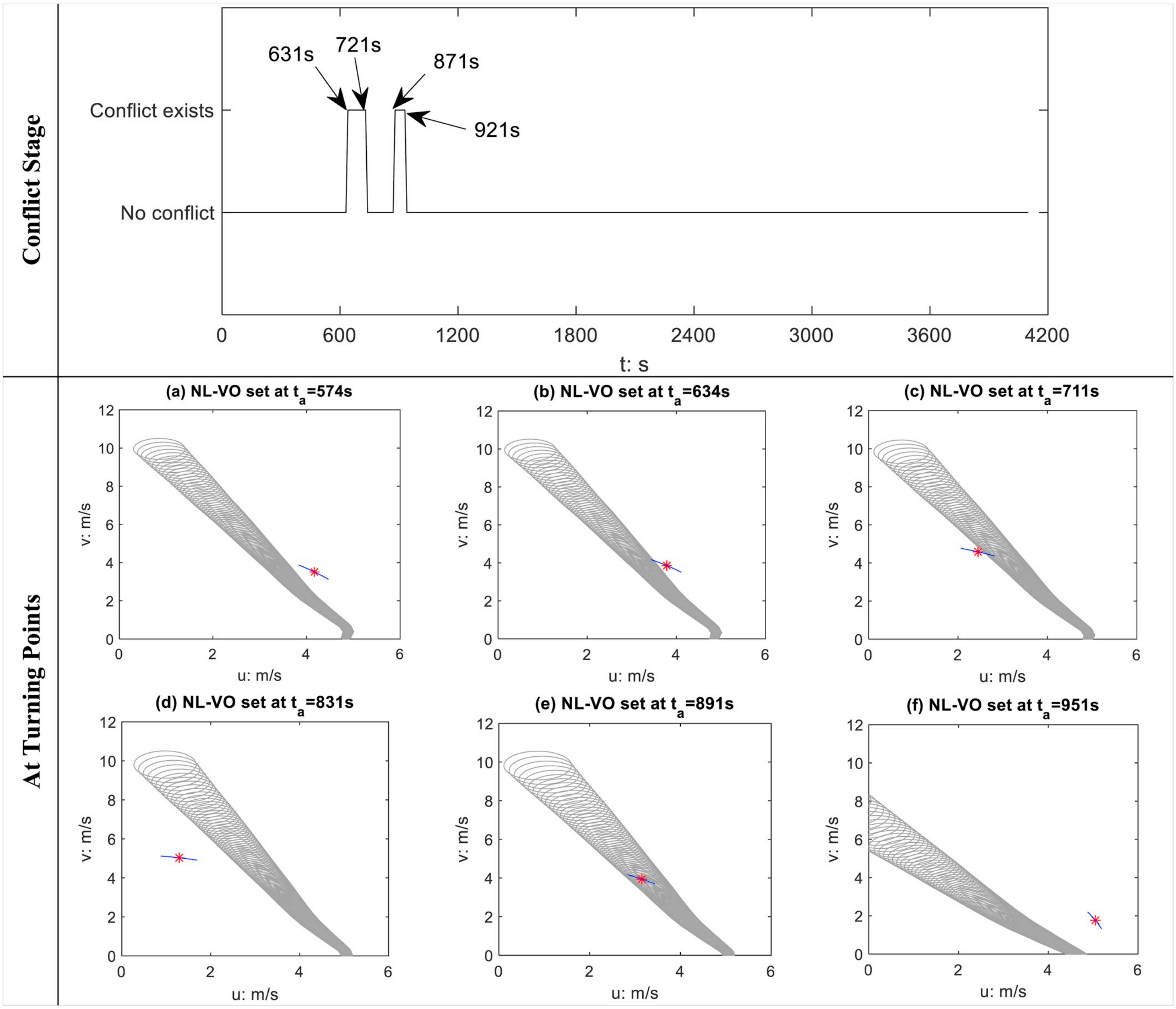

Fig. 12. Conflict detection and ship intention estimation during different encounter stage when Ship1 encounters Ship2 and compression threshold is 15m in multi-vessel encounter scenario.

constant speed. This enables a more accurate analysis of the TS's intention from the OS perspective (Du et al., 2019).

This proposed method has the potential to be applied for various purposes.

One is that the proposed method can be applied to both ex-post analysis and real-time conflict analysis on the condition that the trajectory of OS is known in advance. For the ex-post analysis, the trajectory of OS can be obtained from historical AIS data. However, it is not easy to deal with the raw AIS data due to many erroneous AIS messages (Bailey, 2005; Harati-Mokhtari et al., 2007; Banyś et al., 2012; Huang et al., 2020a). There are two steps to handle raw AIS data that is not 100% accurate. First is the cleaning raw AIS data to improve the quality of AIS data (Felski et al., 2015; Wawruch, 2017; Jaskólski, 2017; Zhao et al., 2018). Second is to set a good compression threshold of DP algorithm to minimize the effects of position errors on the identification of the ship's turning point and maintain the main characteristics of the ship trajectory. Using the historical trajectory of OS recorded in AIS data is only useful for ex-post analysis rather than real-time conflict analysis. There are however possible further development paths to alleviate this current limitation. For instance, a ship trajectory prediction method (Gan et al., 2016; Murray and Perera, 2018; Rong et al., 2019) can be combined with the presented approach, to extend its applicability to real-time conflict assessment. The more accurate the ship's trajectory prediction leads to the more accurate ship intention estimation in the real-time.

Another possible application is supporting the navigators to correct their operation in real-time. Human error is one dominant cause of ship accident (Toffoli et al., 2005; Akyuz and Celik, 2014). The difference between action intention and actual action performance may exist due to the inaccurate estimation of dangerous state or improper operation, timely identification of which can alert the navigator to correct the current operation so as to reduce human error.

Furthermore, the proposed method also contributes to the autonomous shipping development. Reactive elimination of conflict is crucial for autonomous ships (Jokioinen et al., 2016). Autonomous ships need to enable reacting to the unexpected situation quickly to avoid ship conflicts (Maritime, 2018). For instance, when an autonomous ship is confronted with a dangerous situation where other objects do not act properly, the autonomous ship shall have sufficient information, such as understanding other ship's action intention from "first person"

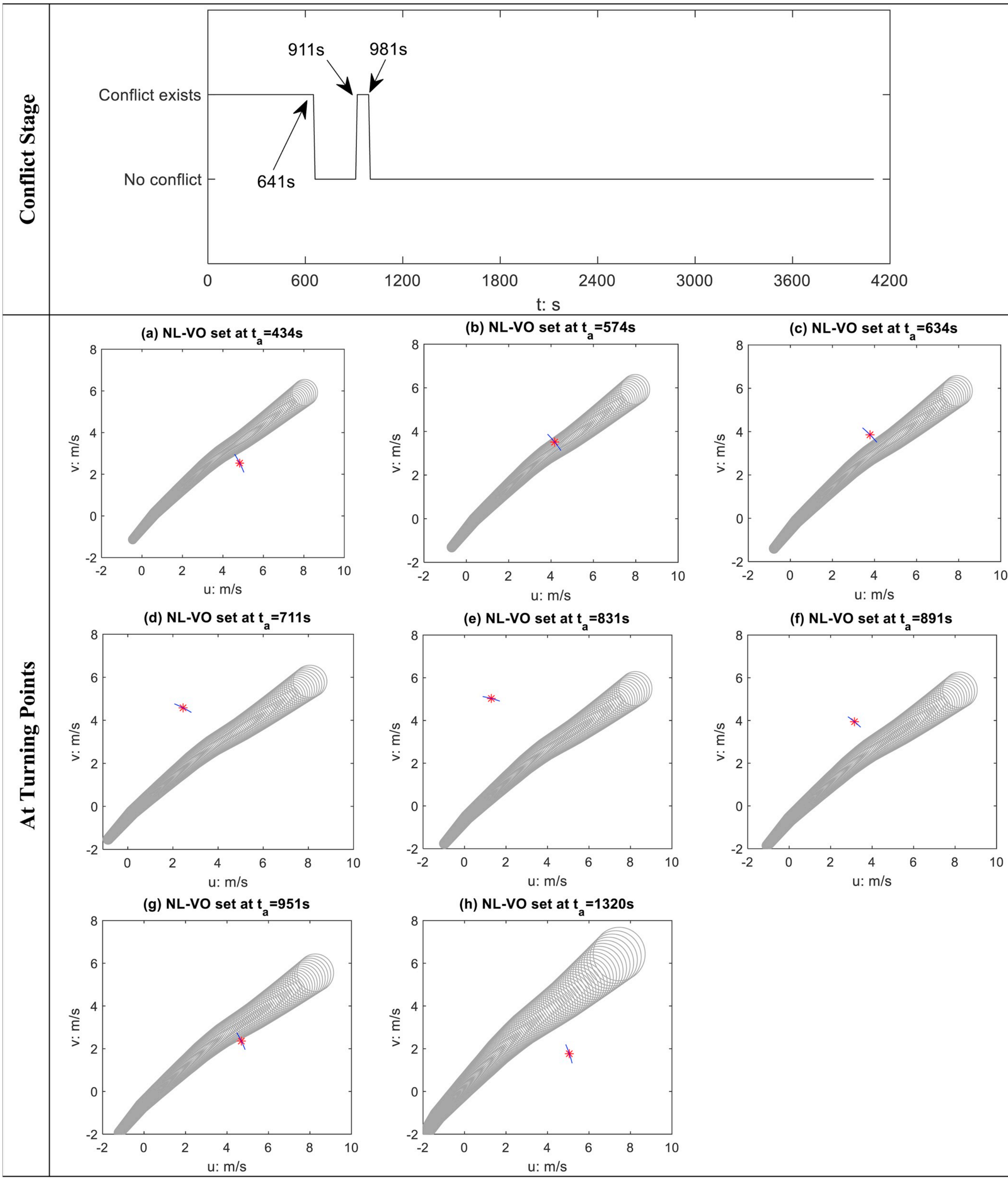

Fig. 13. Conflict detection and ship intention estimation during different encounter stage when Ship1 encounters Ship3 and compression threshold is 15m in multi-vessel encounter scenario.

perspective, to interpret its position and traffic situation, for being as safe as a manned counterpart operating in similar circumstances (Maritime, 2018). However, existing studies (Leedekerken et al., 2014; Wolf et al., 2010) indicate that such issues have not yet been extensively explored (Liu et al., 2016). Although the COLREG is designed for currently manned vessels, and acknowledging that the regulatory implications of introducing autonomous ships are still under discussion, it is apparent that the rules for autonomous ships need to be merged with COLREGs. When the navigation rules for the autonomous ship are determined and merged with COLREGs, the proposed method still has

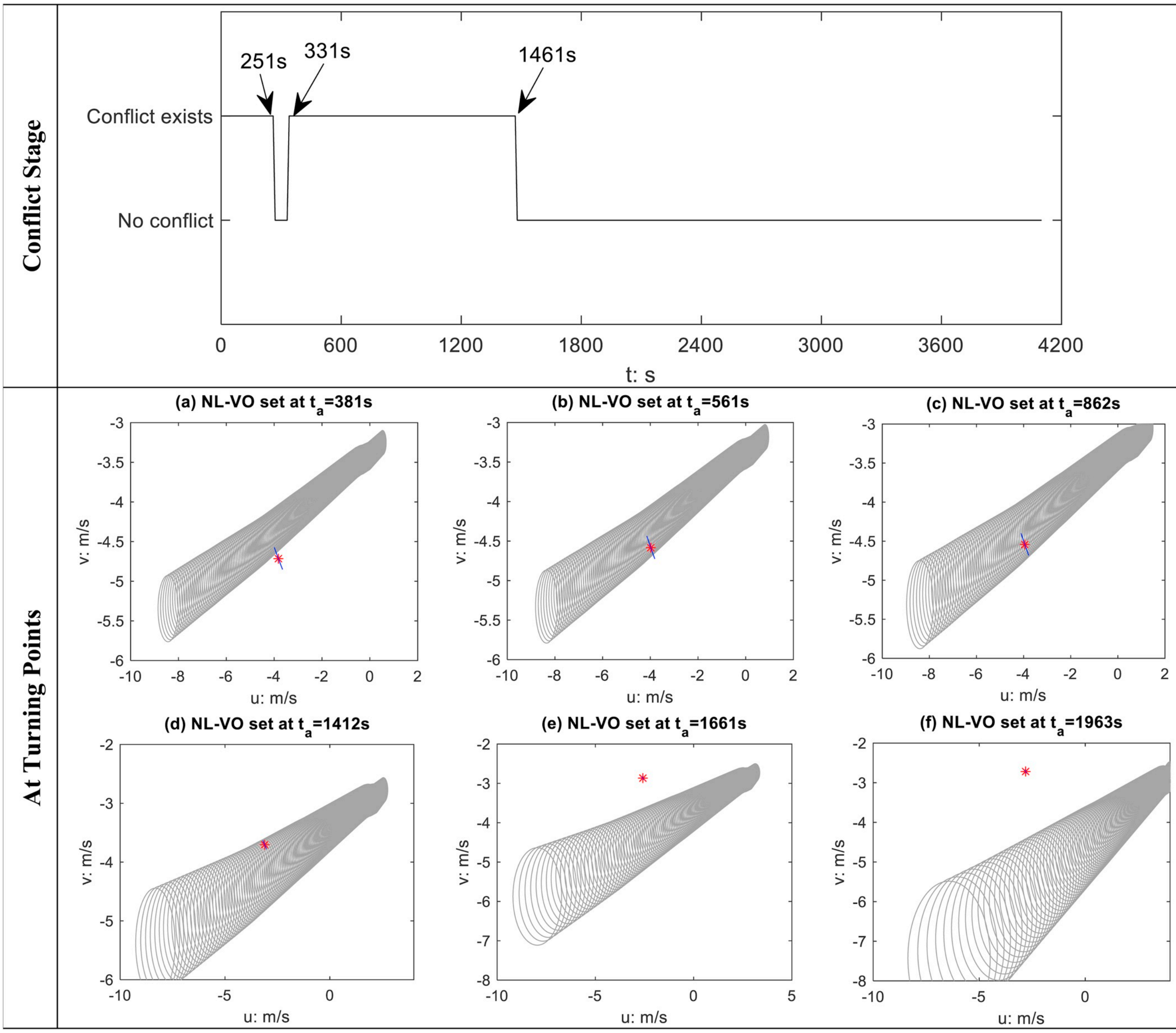

Fig. 14. Conflict detection and ship intention estimation during different encounter stage when Ship2 encounters Ship3 and compression threshold is 15m in multi-vessel encounter scenario.

potential for supporting autonomous ship's safe navigation.

Besides, using this proposed method to estimate the ship intention in a multi-vessel encounter is also feasible, while the TS's action and its corresponding intention should be studied incorporating the contextual situation. From the result of the simulation of multi-vessel encounter in Fig. 12, the Ship1 first turns to port for conflict elimination with Ship3. Even though this evasive action can effectively eliminate the conflict with Ship3, this uncoordinated evasive action causes another conflict between Ship1 and Ship2, and therefore the Ship 2 changes her initial action plan and turns to starboard significantly to eliminate the conflict with Ship 2 and Ship 3. The detected action of Ship1 at 634s is determined as an evasive action for the conflict elimination with Ship 2 and Ship 3 simultaneously. Based on these results, it is plausible that the proposed method can accurately reflect the intentions of the ship action in the conflict elimination process. However, the ship may take evasive action earlier in multi-encounter situations to master the situation (Chauvin and Lardjane, 2008). Incorporating with more external information, including environmental conditions, the dynamic density of ships and behavior of the navigator (Huang et al., 2020b) and ship maneuverability (Li et al., 2019), may contribute to making the ship intention estimation more accurate.

5.2. Sensitivity of compression thresholds in DP algorithm

In the DP algorithm, the compression threshold is critical to both compress redundant information and to maintain the main characteristics of the original trajectory (Zhang et al., 2016a,b). Considering the ship position error in AIS data, too small compression threshold may detect some fake turning points. The ship position data in AIS data is usually from the Global Positioning System (GPS) receiver. The position precision of Differential Global Positioning System (DGPS) is between 2m and 4m for most circumstances (IGNSS, 2013). To minimize the effects of position errors on the identification of the ship's turning point, the size of the compression threshold is suggested to be larger than 4m.

However, as the threshold increases, the remaining characteristic points decrease, and ultimately only terminal tracking points are left (Zhao and Shi, 2019). Missing any critical turning point, especially in a close-range encounter situation, may lead to an inaccurate ship intention estimation. In Zhao and Shi, 2019, the compression effects with different thresholds are illustrated by increasing the threshold value with a fixed step. Therefore, several compression thresholds (5m, 10m, 15m, 20m, 30m, 40m and 50m) were selected in our work to check its compression effect.

Fig. 15 shows the result of the ship action detection and intention estimation on the basis of simplified ship trajectory with different compression thresholds. Almost all the number of detected ship turning points and evasive action points show a decreasing trend with the compression threshold value increasing. The multi-vessel encounter is divided into multiple two-ship encounters. Taking the encounter between Ship2 and Ship3 as an example, the number of detected turning points of Ship3 significantly decreased from 24 to 14 when the compression threshold increased from 5m to 15m. Similarly, the number of identified evasive action points of Ship3 are 9 and 4 respectively when the compression threshold is 5m and 15m. Notably, when the compression threshold increases to 20m, the number of detected evasive action points of Ship3 sharply dropped to 1 because some critical turning points have been deleted. Therefore, in this case, the compression threshold should be smaller than 20m to maintain the main characteristics of the ship trajectory and keep the accuracy of ship action identification and ship intention estimation.

The compression threshold value may vary according to different purposes and the same compression threshold value may have different effects on the detection of ship action points (Zhao& Shi, 2019). Therefore, more knowledge is needed when determining the optimal compression threshold. To make this article concise, we only present the results of ship action identification and ship intention estimation with the compression threshold of 15m, see the case study in Section 4.2.

5.3. Limitations of the proposed method

While the illustrative case studies show promising results, this proposed method is only the first step for the construction of SLoD to reduce the ship conflict probability from the stand-on ship perspective. The aim of the focus is to introduce and present a method which can detect the key actions of the give-way ship from the stand-on ship perspective and then estimate the intention of this action. The case studies illustrate that the model is plausible, but more tests and analyses are still needed. Several issues require further consideration.

Firstly, the uncertainty of the TS's action is simplified to the uncertainty of the change in the TS's course. In this paper, the TS only alters course to eliminate conflict, which is however a quite stringent simplification compared to real processes of elimination of conflict. Many factors can cause voluntary and involuntary speed loss during navigation, such as wind resistance and steering. The omission of ship speed reduction during the ship steering can lead to an inaccurate estimation of reachable ship velocity and misjudgment of conflict, which may have important implications for the understanding of the ship action intention. Another issue is that the response time from the initial rudder angle to the specified rudder angle is ignored, which is not fully realistic. Considering the corresponding time of the ship's rudder angle, the ship's steering will be relatively stable instead of drastic, and the ship's action change characteristics will be weakened. This adopted method needs to be further tested and improved to guarantee the accurate identification of the TS's action and understand her intention, which can be alleviated by utilizing a more elaborate ship maneuvering model compared to the Nomoto model applied in this paper. The major innovation of this article is not using a Nomoto model but proposes a framework of improving stand-on ship's situational awareness by estimating the intention of the give-way ship, which means if the MMG model or Abkowitz's model is available, this proposed framework also can be applied to analyze the intention of the ship.

Secondly, the criteria of ship intention estimation need to be further improved. In this work, the ship intention is divided as evasive action and normal navigation by considering conflict. The severity of ship conflict needs to be further subdivide. Quantifying the relationship between ship action and conflict contributes to better understand the ship action intention. Besides, more testing is needed to affirm the applicability and reliability of the DP-algorithm to understand stand-on ship actions. The ship position error caused by the GPS receiver also affects the accuracy of the ship trajectory data. Therefore, the selected compression threshold for application of the DP algorithm to identify the ship action points is quite important. The proper selection of a compression threshold in DP algorithm can not only lower the inaccuracy of ship action identification caused by inaccurate ship position, but also can avoid the non-detection of critical turning points. From the sensitivity analysis in Fig. 15, the compression effect is different under different compression thresholds. Therefore, the determination of upper and lower bounds of a proper compression threshold still needs further work to make it more precise.

Additionally, it is not considered whether the TS takes proper evasive action. The action quality assessment is also crucial for OS's decision making, see Fig. 2. Even though the TS has taken evasive action, this does not necessarily mean this action is appropriate. Taking the evasive action timely and choosing a substantial action to keep well clear is also

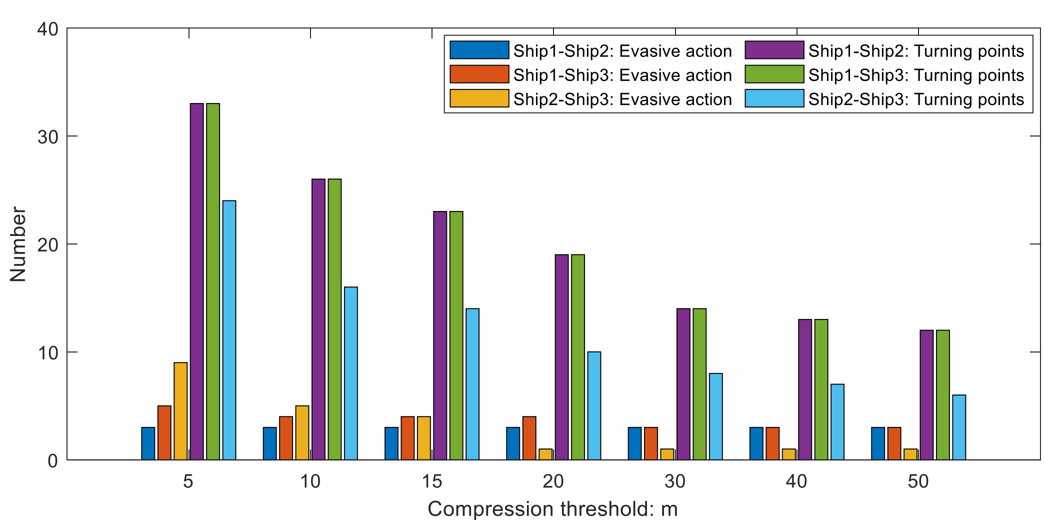

Fig. 15. The number of detected ship turning points and evasive action points with different compression thresholds in multi-vessel encounter scenario.

vital, as described in the COLREGs. The misunderstanding of TS's action may lead to an uncoordinated ship action from OS's viewpoint. For OS, taking action too late is characterized by the fact that only a limited number of maneuvering options remains, while taking evasive action too early may violate Rule 17 in the COLREGs. There is a need to assess the quality of ship action, which is the next step of construction of SLoD. One plausible way to solve this is to further refine the conflict severity. Quantifying multiple risk levels can help to establish a more accurate quantitative relationship between ship action and conflict, which may be beneficial to better understand TS's intention. For instance, the conflict can be ranked in combination with the number of maneuvering options remains and subdivided into four levels corresponding to four stages in the COLREGs (He et al., 2017), which could be beneficial for OS to determine when she is permitted or required to take action for elimination of conflict.

6. Conclusion

The lack of situational awareness has been identified as an important contributing factor to ship conflicts. While the International Regulations for Preventing Collision at Sea (COLREGs) significantly contribute to navigation safety, the COLREGs do not provide specific guidance in terms of concrete limit values in actual operation, especially for the stand-on ship. Proper risk anticipation from the stand-on ship for planning evasive actions is critical for successful elimination of conflict. To improve OS's situational awareness, the estimation of TS's intention is critical. However, there currently is a lack of methods which specifically focuses on this aspect of ship encounters. This paper proposes a method to estimate TS's intention, which can be treated as the basis for the construction of a "Stand-on Ship as Second Line of Defense" (SLoD) to reduce the ship collision probability. The dynamic nature of ship action is measured by utilizing NL-VO algorithm to assess the conflict. The uncertainty of ship action during the dangerous encounter process is considered based on its ship maneuverability. Through this proposed method, the TS's action characteristics and the corresponding intention at different encounter stages are quantitatively identified.

The case studies illustrate that it is plausible to use this proposed method to estimate the TS's action intention both in the ship-pair encounter scenarios and multi-vessel encounter scenarios, but more tests and analyses are still needed. Several issues require further consideration. First, the criteria of ship intention estimation need to be further improved in future research, including the selection of a proper compression threshold of the DP algorithm. Second, the uncertainty of TS's action needs to be considered more comprehensive to improve the accuracy of TS's action intention. Furthermore, how the understanding of TS's action intention is converted to instruct OS's decision making for involving into the conflict needs further work on ship action quality assessment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Lei Du: Conceptualization, Methodology, Data curation, Writing - original draft, Visualization, Formal analysis, Writing - review & editing. **Floris Goerlandt:** Supervision, Writing - review & editing, Investigation. **Osiris A. Valdez Banda:** Supervision, Writing - review & editing, Investigation. **Yamin Huang:** Conceptualization, Methodology, Writing - review & editing, Formal analysis. **Yuanqiao Wen:** Supervision. **Pentti Kujala:** Supervision, Resources, Funding acquisition, Project administration.

Acknowledgements

This work was supported by China Scholarship Council (Grant Number: 201606950009), National Science Foundation of China (Grant Number: 51709218) and RESET project. RESET has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 730888. The work presented in this article is part of the Design for Value (D4 Value) program. The D4 Value program is partially funded by the Finnish Funding Agency for Innovation (TEKES). The contributions of the second author are supported by the project 'Safe Navigation and Environmental Protection', funded through the Ocean Frontier Institute based on funding from the Canada First Research Excellence Fund.

List of abbreviations

COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
ConfP	Conflict Positions
CPA	Closest Point of Approach
CTPA	Collision Threat Parameters Area
DCPA	Distance to the Closest Point of Approach
D-P algorithm	Douglas-Peucker algorithm
EMSA	European Maritime Safety Agentcy
FLoD	Give-way ship as First Line of Defense
GPS	Global Positioning System
DGPS	Differential Global Positioning System
LLoD	Last Line of Defense
MMG	Maneuvering Modeling Group
NL-VO	Non-Linear VO
LTTA	Last Time to Take Action
MDTC	Minimum Distance to Collision
OS	Own Ship
ROT	Rate of Turn
SD	Ship Domains
SLoD	Stand-on Ship as Second Line of Defense
TCPA	Time to CPA
TLoD	Both ships as Third Line of Defense

TS	Target Ship
TSS	Traffic Separation Schemes
VO	Velocity Obstacles

List of notation

C	ship course
IP_{TS}	initial position of the TS
K	turning ability index
L	ship length, the subscript i is TS and OS
$P(x,y,t)$	ship position, the subscript i is TS and OS
R	the radius of circular-shape prohibit region around the OS
RV	reachable velocity set
r	the yaw rate
$\dot{r}$	acceleration of yaw rate
T	turning lag index
$TP_{TS}\{tp_1, tp_2, ...tp_t, ...\}$	turning points of the give-way ship
t_a	the time of evasive action
t_{as}	starting point of evasive action
t_{ae}	ends point of evasive action
tp	time of each turning points
t_r	the time that conflict exists
t_{rs}	the starting moment of conflict stage
t_{re}	the ending moment of conflict stage
U_{NL-VO}	NL-VO set
$u_{TS}(t)$	the current ship speed $\overrightarrow{V}_{TS}(t)$ in the direction of OX coordinate
$v_{TS}(t)$	the current ship speed $\overrightarrow{V}_{TS}(t)$ in the direction of OY coordinate
$\overrightarrow{V}$	Ship speed
V_{TS}	the magnitude of ship speed $\overrightarrow{V}_{TS}$
φ	magnitude of course change
δ	demanded rudder angle
Δt	time step of simulation

Appendix

Table 1
Pseudo code for D-P algorithm based on Douglas and Peucker (1973).

D-P algorithm
Input: Ship trajectory TR_TS = {$P1$, $P2$, $P3$, …, Pn}, Compression threshold ζ
Parameters: *d*(distance), *dmax*(maximum distance), index, TP_TS (turning points set)
Initial set: *m* = *n, dmax=0, index* = 1
for i = 2 to i=(m-1)
$P_s = P1$//Starting point is marked as P_s
$P_e = P_m$//*End point is marked as* P_e
//Searching for the farthest point to the TR connecting P_s with P_e
d = Perpendicular Distance ($P[i]$, Line(P_s, P_e))
if $d > dmax$
index = i
$dmax = d$
end if
end for
if $dmax >$ ζ
//Spliting the ship trajectory into two sub-tracks if the farthest point *Pindex* exceeds the Compression threshold ζ
TP1 = { P_s, …, Pindex}
TP2 = {Pindex, …, P_e }
TP_TS = [TP1, TP2]
else
TP_TS = [P_s, P_e]
end if
return TP_TS

References

Akyuz, E., Celik, M., 2014. Utilisation of cognitive map in modelling human error in marine accident analysis and prevention. Saf. Sci. 70, 19–28.

Bailey, N., 2005. Training, Technology and AIS: looking beyond the box. In: Proceedings of the Seafarers International Research Centre's 4th International Symposium Cardiff University, Cardiff, pp. 108–128.

Baldauf, M., Mehdi, R., Fischer, S., Gluch, M., 2017. A Perfect Warning to avoid collisions at sea? Sci. J. Maritime Univ. Szczecin 49 (121), 53–64.

Banazadeh, A., Ghorbani, M.T., 2013. Frequency domain identification of the Nomoto model to facilitate Kalman filter estimation and PID heading control of a patrol vessel. Ocean Eng. 72, 344–355.
Banyś, P., Noack, T., Gewies, S., 2012. Assessment of AIS vessel position report under the aspect of data reliability. Annu. Navig. 19 (1), 5–16.
Blaich, M., Rosenfelder, M., Schuster, M., Bittel, O., Reuter, J., 2012. Extended grid based collision avoidance considering colregs for vessels. IFCA. Proc. Vol. 45 (27), 416–421.
Carrillo, S., Contreras, J., 2018. Obtaining first and second order Nomoto models of a fluvial support patrol using identification techniques. Ship. Sci. Technol. 11 (22), 19–28.
Chauvin, C., Lardjane, S., 2008. Decision making and strategies in an interaction situation: collision avoidance at sea. Transport. Res. F Traffic Psychol. Behav. 11 (4), 259–269.
Chen, P., Huang, Y., Mou, J., van Gelder, P.H.A.J.M., 2018. Ship collision candidate detection method: a velocity obstacle approach. Ocean Eng. 170, 186–198.
China Maritime Safety Administration, 2018. Report on the investigation of the collision between M.T. Sanchi and M.V. CF crystal in east China sea on 6 january 2018 (China MSA, 2018). Retrieved from. https://www.mardep.gov.hk/en/msnote/pdf/msin1817anx1.pdf.
Cho, Y., Han, J., Kim, J., 2018. Intent inference of ship maneuvering for automatic ship collision avoidance. IFAC-PapersOnLine 51 (29), 384–388.
Debnath, A.K., Chin, H.C., 2010. Navigational traffic conflict technique: a proactive approach to quantitative measurement of collision risks in port waters. J. Navig. 63 (1), 137–152.
Douglas, D.H., Peucker, T.K., 1973. Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. Cartographica: Int. J. Geogr. Inf. Geovisualization 10 (2), 112–122.
Du, L., Goerlandt, F., Kujala, P., 2019. Review and Analysis of Methods for Assessing Maritime Waterway Risk Based on Non-accident Events Detected from AIS Data. Reliability Engineering & System Safety (Under review).
EMSA, 2018. Annual Overview of Marine Casualties and Incidents 2018. European Maritime Safety Agency. Retrieved from. http://www.emsa.europa.eu/news-a-press-centre/external-news/download/5425/3406/23.html.
Fan, J.M., Nuyujukian, P., Kao, J.C., Chestek, C.A., Ryu, S.I., Shenoy, K.V., 2014. Intention estimation in brain–machine interfaces. J. Neural. Eng. 11 (1), 016004.
Felski, A., Jaskólski, K., Banyś, P., 2015. Comprehensive assessment of automatic identification system (AIS) data application to anti-collision manoeuvring. J. Navig. 68 (4), 697–717.
Fossen, T.I., 2011. Handbook of Marine Craft Hydrodynamics and Motion Control. John Wiley & Sons.
Gale, H., Patraiko, D., 2007. Improving Navigational Safety. The Role of E-Navigation. Seaways, pp. 4–8.
Gan, Shaojun, Liang, Shan, Kang, Li, Deng, Jing, Cheng, Tingli, 2016. Ship trajectory prediction for intelligent traffic management using clustering and ANN. In: 2016 UKACC 11th International Conference on Control (CONTROL). IEEE, pp. 1–6, 2016.
Goerlandt, F., Montewka, J., Lammi, H., Kujala, P., 2012a. Analysis of Near Collisions in the Gulf of Finland. Advances in Safety. Reliability and Risk Management, pp. 2880–2886.
Goerlandt, F., Ståhlberg, K., Kujala, P., 2012b. Influence of impact scenario models on collision risk analysis. Ocean Eng. 47, 74–87.
Goerlandt, F., Montewka, J., Kuzmin, V., Kujala, P., 2015. A risk-informed ship collision alert system: framework and application. Saf. Sci. 77, 182–204.
Hänninen, M., 2014. Bayesian networks for maritime traffic accident prevention: benefits and challenges. Accid. Anal. Prev. 73, 305–312.
Harati-Mokhtari, A., Wall, A., Brooks, P., Wang, J., 2007. Automatic Identification System (AIS): data reliability and human error implications. J. Navig. 60 (3), 373–389.
He, Y., Jin, Y., Huang, L., Xiong, Y., Chen, P., Mou, J., 2017. Quantitative analysis of COLREG rules and seamanship for autonomous collision avoidance at open sea. Ocean Eng. 140, 281–291.
Hong, Biguang, Yang, Yu, 2000. Ship's K, T indices statistics analysis. J. Dalian Marit. Univ. 26, 29–33.
Huang, Y., van Gelder, P.H.A.J.M., 2017. Non-linear velocity obstacles with applications to the maritime domain. In: Maritime Transportation and Harvesting of Sea Resources. CRC Press Lisbon, Portugal, pp. 999–1007.
Huang, Y., van Gelder, P.H.A.J.M., 2019. Time-varying risk measurement for ship collision prevention. Risk Anal. 40 (1), 24–42.
Huang, S., Su, X., Hu, Y., Mahadevan, S., Deng, Y., 2014. A new decision-making method by incomplete preferences based on evidence distance. Knowl. Base Syst. 56, 264–272.
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.
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, L., Wen, Y., Guo, W., Zhu, X., Zhou, C., Zhang, F., Zhu, M., 2020a. Mobility pattern analysis of ship trajectories based on semantic transformation and topic model. Ocean Eng., 107092
Huang, Y., Chen, L., Chen, P., Negenborn, R.R., van Gelder, P.H.A.J.M., 2020b. Ship collision avoidance methods: state-of-the-art. Saf. Sci. 121, 451–473. https://doi.org/10.1016/j.ssci.2019.09.018.
IGNSS, 2013. Precise Positioning Services in the Maritime Sector. International Global Navigation Satellite Systems. Retrieved from. http://www.ignss.org/LinkClick.aspx?fileticket=b%2F3x6KEaFS4%3D&tabid=56.
Jaskólski, K., 2017. Two-dimensional coordinate estimation for missing Automatic Identification System (AIS) signals based on the discrete Kalman filter algorithm and Universal Transverse Mercator (UTM) projection. 52Sci. J. Marit. Univ. Szczecin. 52, 82–89.
Johansen, T.A., Perez, T., Cristofaro, A., 2016. Ship collision avoidance and COLREGS compliance using simulation-based control behavior selection with predictive hazard assessment. IEEE Trans. Intell. Transport. Syst. 17 (12), 3407–3422.
Jokioinen, E., Poikonen, J., Jalonen, R., Saarni, J., 2016. Remote and Autonomous Ships-The Next Steps. AAWA Position Paper, Rolls Royce plc, London.
Journee, J.M.J., 1970. A simple method for determining the manoeuvring indices k and t from zigzag trial data. Transl. Rep. 267, 1–9.
Kim, K.I., Jeong, J.S., Lee, B.G., 2017. Study on the analysis of near-miss ship collisions using logistic regression. J. Adv. Comput. Intell. Intell. Inf. 21 (3), 467–473.
Krata, P., Montewka, J., 2015. Assessment of a critical area for a give-way ship in a collision encounter. Arch. Transport. 34 (2), 51–60.
Large, F., Sekhavat, S., Shiller, Z., Laugier, C., 2002. Towards real-time global motion planning in a dynamic environment using the NLVO concept. In: Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on, vol. 1. IEEE, pp. 607–612.
Leedekerken, J.C., Fallon, M.F., Leonard, J.J., 2014. Mapping complex marine environments with autonomous surface craft. In: Experimental Robotics. Springer, Berlin, Heidelberg, pp. 525–539.
Lei, P.R., Tsai, T.H., Wen, Y.T., Peng, W.C., 2017. A framework for discovering maritime traffic conflict from AIS network. In: Network Operations and Management Symposium (APNOMS), 2017 19th Asia-Pacific. IEEE, pp. 1–6.
Li, S., Liu, J., Negenborn, R.R., 2019. Distributed coordination for collision avoidance of multiple ships considering ship maneuverability. Ocean Eng. 181, 212–226.
Liu, Z., Wu, Z., 2004. A method for human reliability analysis in collision avoidance of ships. In: Third International Conference on Collision and Grounding of Ships (ICCGS), vol.143, p. 150.
Liu, Z., Zhang, Y., Yu, X., Yuan, C., 2016. Unmanned surface vehicles: an overview of developments and challenges. Annu. Rev. Contr. 41, 71–93.
Maritime, U.K., 2018. Maritime autonomous surface ships - UK code of practice. Retrieved from. https://www.maritimeuk.org/documents/305/MUK_COP_2018_V2_B8rlgDb.pdf.
Meratnia, N., Rolf, A., 2004. Spatiotemporal compression techniques for moving point objects. In: International Conference on Extending Database Technology. Springer, Berlin, Heidelberg, pp. 765–782.
Mestl, T., Tallakstad, K.T., Castberg, R., 2016. Identifying and analyzing safety critical maneuvers from high resolution AIS data. TransNav: Int. J. Mar. Navig. Saf. Sea. Transport. 10 (1), 69–77.
Mochizuki, Y., & Ishikawa, K., 2015. U.S. Patent No. 9,177,477. Washington, DC: U.S. Patent and Trademark Office.
Montewka, J., Przemyslak, K., 2014. Towards the assessment of a critical distance between two encountering ships in open waters. Eur. J. Navig. 12 (3), 7–14.
Montewka, J., Hinz, T., Kujala, P., Matusiak, J., 2010. Probability modelling of vessel collisions. Reliab. Eng. Syst. Saf. 95 (5), 573–589.
Mou, J., Chen, P., Yixiong, H.E., Zhang, X., Zhu, J., Rong, H., 2018. Fast self-tuning spectral clustering algorithm for ais ship trajectory. J. Harbin Eng. Univ. 39 (3), 428–432.
Muckell, J., Hwang, J.H., Lawson, C.T., Ravi, S.S., 2010. Algorithms for compressing GPS trajectory data: an empirical evaluation. In: Proceedings of the 18th SIGSPATIAL International Conference on Advances in Geographic Information Systems. ACM, pp. 402–405.
Muckell, J., Olsen, P.W., Hwang, J.H., Lawson, C.T., Ravi, S.S., 2014. Compression of trajectory data: a comprehensive evaluation and new approach. GeoInformatica 18 (3), 435–460.
Murray, B., Perera, L.P., 2018. A data-driven approach to vessel trajectory prediction for safe autonomous ship operations. In: 2018 Thirteenth International Conference on Digital Information Management (ICDIM). IEEE, pp. 240–247.
Nomoto, K., Taguchi, K., Honda, K., Hirano, S., 1956. On the steering qualities of ships. J. Zosen Kiokai 1956 (99), 75–82.
Omori, T., Yokoyama, A., Okada, H., Ishikawa, S., Nagata, Y., 2007. Computational modeling of human-robot interaction based on active intention estimation. In: International Conference on Neural Information Processing. Springer, Berlin, Heidelberg, pp. 185–192.
Park, J., Kim, J., 2017. Predictive evaluation of ship collision risk using the concept of probability flow. IEEE J. Ocean. Eng. 42 (4), 836–845.
Park, J., Han, J., Kim, J., Son, N.S., 2016. Probabilistic quantification of ship collision risk considering trajectory uncertainties. IFAC-PapersOnLine 49 (23), 109–114.
Perera, L.P., Oliveira, P., Soares, C.G., 2011. Dynamic parameter estimation of a nonlinear vessel steering model for ocean navigation. In: ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering. American Society of Mechanical Engineers, pp. 881–888.
Qu, X., Meng, Q., Suyi, L., 2011. Ship collision risk assessment for the Singapore Strait. Accid. Anal. Prev. 43 (6), 2030–2036.
Ren, R.Y., Zou, Z.J., Wang, Y.D., Wang, X.G., 2018. Adaptive Nomoto model used in the path following problem of ships. J. Mar. Sci. Technol. 23 (4), 888–898.
Rong, H., Teixeira, A.P., Soares, C.G., 2019. Ship trajectory uncertainty prediction based on a Gaussian Process model. Ocean Eng. 182, 499–511.
Sormunen, O.V.E., Goerlandt, F., Häkkinen, J., Posti, A., Hänninen, M., Montewka, J., Ståhlberg, K., Kujala, P., 2015. Uncertainty in maritime risk analysis: extended case study on chemical tanker collisions. Proc. IME M J. Eng. Marit. Environ. 229 (3), 303–320.
Szlapczynski, R., Krata, P., 2018. Determining and visualizing safe motion parameters of a ship navigating in severe weather conditions. Ocean Eng. 158, 263–274.

Tao, J., Du, L., Dehmer, M., Wen, Y., Xie, G., Zhou, Q., 2019. Path following control for towing system of cylindrical drilling platform in presence of disturbances and uncertainties. ISA Trans. 95, 185–193.
Toffoli, A., Lefevre, J.M., Bitner-Gregersen, E., Monbaliu, J., 2005. Towards the identification of warning criteria: analysis of a ship accident database. Appl. Ocean Res. 27 (6), 281–291.
Ulusçu, Ö.S., Özbaş, B., Altıok, T., Or, İ., 2009. Risk analysis of the vessel traffic in the strait of Istanbul. Risk Anal.: Int. J. 29 (10), 1454–1472.
van den Broek, B., Smith, A., den Breejen, E., van de Voorde, I., 2014. Inference of vessel intent and behaviour for maritime security operations. In: Unmanned/Unattended Sensors and Sensor Networks X, vol.9248. International Society for Optics and Photonics, p. 92480E.
van Iperen, E., 2012. Detection of hazardous encounters at the North Sea from AIS data. In: The International Workshop on Next Generation of Nautical Traffic Model, Shanghai.
Wang, N., 2010. An intelligent spatial collision risk based on the quaternion ship domain. J. Navig. 63 (4), 733–749.
Wawruch, R., 2017. Ability to test shipboard automatic identification system instability and inaccuracy on simulation devices. Sci. J. Marit. Univ. Szczecin. 52, 128–134.
Weng, J., Xue, S., 2015. Ship collision frequency estimation in port fairways: a case study. J. Navig. 68 (3), 602–618.
Weng, J., Meng, Q., Qu, X., 2012. Vessel collision frequency estimation in the Singapore Strait. J. Navig. 65 (2), 207–221.
Wolf, M.T., Assad, C., Kuwata, Y., Howard, A., Aghazarian, H., Zhu, D., Lu, T., Trebi-Ollennu, A., Huntsberger, T., 2010. 360-degree visual detection and target tracking on an autonomous surface vehicle. J. Field Robot. 27 (6), 819–833.
Wu, X., Mehta, A.L., Zaloom, V.A., Craig, B.N., 2016. Analysis of waterway transportation in Southeast Texas waterway based on AIS data. Ocean Eng. 121, 196–209.
Wu, B., Cheng, T., Yip, T.L., Wang, Y., 2020. Fuzzy Logic Based Dynamic Decision-Making System for Intelligent Navigation Strategy within Inland Traffic Separation Schemes, vol.197, p. 106909.
Zhang, X.G., Zou, Z.J., 2011. Identification of Abkowitz model for ship manoeuvring motion using ε-support vector regression. J. Hydrodyn. 23 (3), 353–360.
Zhang, J., Yan, X., Chen, X., Sang, L., Zhang, D., 2012. A novel approach for assistance with anti-collision decision making based on the International Regulations for Preventing Collisions at Sea. Proc. IME M J. Eng. Marit. Environ. 226 (3), 250–259.
Zhang, W., Goerlandt, F., Kujala, P., Wang, Y., 2016a. An advanced method for detecting possible near miss ship collisions from AIS data. Ocean Eng. 124, 141–156.
Zhang, S.K., Liu, Z.J., Cai, Y., Wu, Z.L., Shi, G.Y., 2016b. AIS trajectories simplification and threshold determination. J. Navig. 69 (4), 729–744.
Zhao, L., Shi, G., 2018. A method for simplifying ship trajectory based on improved Douglas–Peucker algorithm. Ocean Eng. 166, 37–46.
Zhao, L., Shi, G., 2019. A trajectory clustering method based on Douglas-Peucker compression and density for marine traffic pattern recognition. Ocean Eng. 172, 456–467.
Zhao, L., Shi, G., Yang, J., 2018. Ship trajectories pre-processing based on AIS data. J. Navig. 71 (5), 1210–1230.
Zhu, F.X., Miao, L.M., Liu, W., 2014. Research on vessel trajectory multi-dimensional compression algorithm based on douglas-peucker theory. In: Applied Mechanics and Materials, vol.694. Trans Tech Publications, pp. 59–62.
Zhu, M., Hahn, A., Wen, Y.Q., 2018. Identification-based controller design using cloud model for course-keeping of ships in waves. Eng. Appl. Artif. Intell. 75, 22–35.
Zhuo, Y., Tang, T., 2008. An intelligent decision support system to ship anti-collision in multi-ship encounter. In: 2008 7th World Congress on Intelligent Control and Automation. IEEE, pp. 1066–1071.