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Velocity obstacle algorithms for collision prevention at sea

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ABSTRACT

It is of critical importance to prevent collisions at sea for navigation safety. Some popular techniques have been proposed and been used in practice, e.g. closest point of approach, collision threat parameters area, etc. However, most of these techniques assume that the target ship keeps a constant velocity which is unrealistic and may easily lead to a false alarm. In this article, Velocity Obstacle (VO) algorithms are applied to support collision avoidance with target ships whose trajectories are non-linear (with time-dependent velocities) and (probabilistically) predictable. In particular, Linear-VO, Non-Linear VO, and Probabilistic VO algorithms are used for this purpose. Compared to traditional approaches, these algorithms are capable of detecting collision dangers with target ships sailing non-linearly and (probabilistically) predictably, finding collision-free velocities in multi-ship scenarios, and preventing collisions. Two scenarios are designed to demonstrate the performance of VO algorithms. The results show that the proposed VO algorithms can facilitate collision detection and offer proper collision-free solutions for ships.

1. Introduction

Ship collision is one major threat to navigation safety at sea. It usually results in dramatic financial loss and environmental pollution. Moreover, the safety of crews on board is also under threat. An active solution to prevent these losses is reducing the probability of collision. The research focusing on this theme is known as collision prevention. Researchers in this field are dedicated to finding methods to detect collision dangers as early as possible and to find proper collision-free solutions.

In practice, one of the most widely used methods is based on "Closest Point of Approach" (CPA). CPA is an estimated closest position of an approaching ship. Two indicators are usually used in CPA criterion, namely Distance to CPA (DCPA) and Time to CPA (TCPA). DCPA shows the smallest distance between own ship and the approaching ship; TCPA provides the remaining time for the approaching ship sailing to CPA. When these indicators are smaller than certain thresholds, a collision warning is given. To support practical evasive actions, various factors have been integrated into the CPA criterion by researchers (Hilgert and Baldauf, 1997), e.g. sailing regulation (like International Regulations for Preventing Collisions at Sea), ships' dimension, movement information, etc. As a result, the CPA criterion is able to raise a collision alarm in compliance with sailing regulations and seamanship. To date, CPA indicators have been embedded in radar systems on board in support of collision avoidance, namely Automatic Radar Plotting Aid (ARPA).

Although the CPA method is widely accepted both in practice and in academia, it has some pitfalls. Firstly, the shape of the ship is simplified as a point, which might result in overestimation of feasible time for steering. That is to say, a collision can happen before the ship reaches the CPA (Szlapczynski and Szlapczynska, 2016). Secondly, the CPA approach does not directly provide evasive suggestions. Instead, the crew has to perform digital evasive actions in ARPA and observe the changes of CPA. The final evasive actions are determined based on these trails in ARPA. This process is time-consuming. In urgent situations, it is difficult to find an evasive action in this way. Thirdly, this method frequently leads to false alarms (Goerlandt et al., 2015). The calculation of CPA is based on an assumption that the other ship keeps the observed velocity in the future. However, the motion of the ship is hard to be invariant, especially when the ship is affected by external disturbances or is taking evasive actions. In return, the estimated CPA is changing over time, which may lead to false collision alarms.

Numerous studies have been carried out to overcome these pitfalls. In order to consider the shape of ships in collision detection and avoidance, "ship domain" (Pietrzykowski and Uriasz, 2009; Szlapczynski and Szlapczynska, 2016), "collision diameter" (Fujii and Shiobara, 1971; Pedersen, 1995) and "minimum distance to collision" (Montewka et al., 2010) have been introduced as alternatives. For detailed information,

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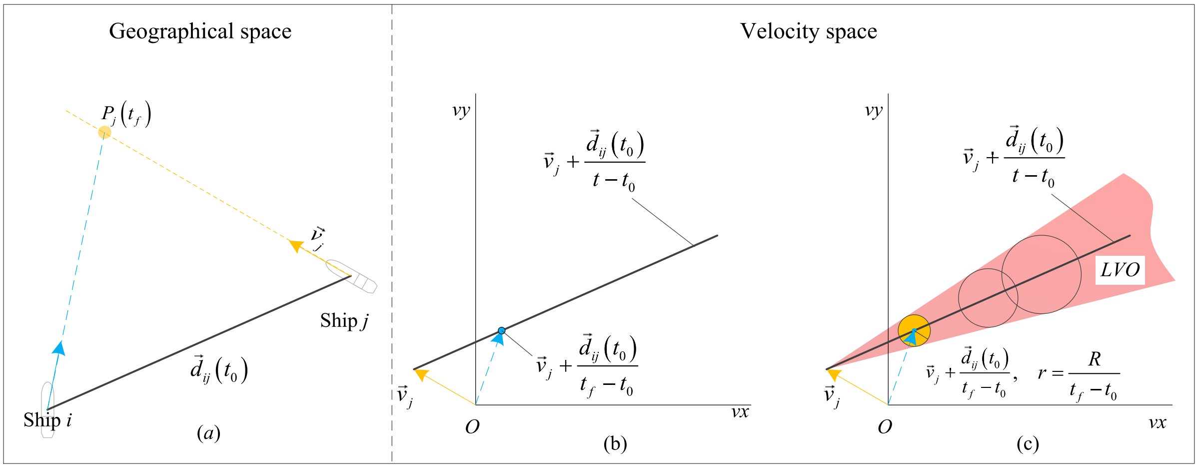

Fig. 1. Illustration of Linear VO set (note: (a) is geographical display of the scenario; (b) is the LVO set neglecting the dimension of ship; (c) LVO considering the dimension of ship).

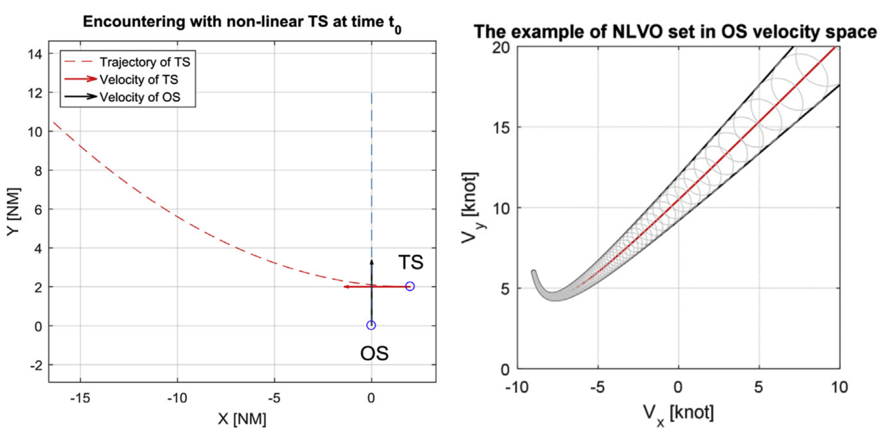

Fig. 2. Illustration of NLVO set (note: (a) is geographical display of the encounter scenario; (b) is NLVO considering the dimension of ship).

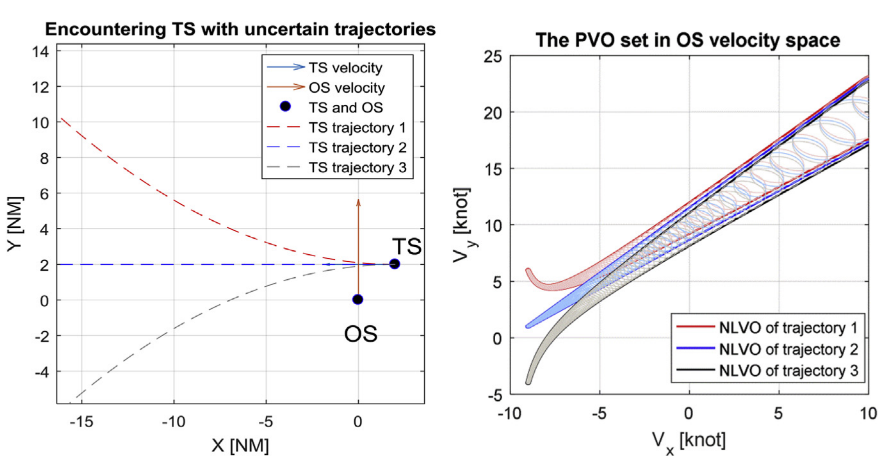

Fig. 3. Illustration of PVO set (note: (a) is geographical display of the scenario with three possible TS's trajectories; (b) is the envelope of PVO set).

readers can refer to (Szlapczynski and Szlapczynska, 2017b), (Zhang et al., 2012), and (Krata and Montewka, 2015).

For the convenience of searching evasive actions, Collision Threat Parameters Area (CTPA) is introduced. CTPA collects a set of velocities that leads one ship (or own ship) to collide with other ships (or target ship) (Degre and Lefevre, 1981; Lenart, 1983). This set is known as CTPA. When the velocity of the own ship is belonging to a CTPA set, a collision alarm is raised. Additionally, all the velocities outside of this set are collision-free solutions. Pedersen et al. (2003) showed that this approach facilitates more homogeneous, precise and safe evasive maneuvers. Moreover, combining with navigation regulations (Szlapczynski and Szlapczynska, 2015) and ship domains (Szlapczynski, 2008), this method shows a great potential in the field of maritime research (Szlapczynski and Szlapczynska, 2017a). However, like the most of existing prevention methods, the CTPA method assumes that the target ship travels in a straight line at a constant speed (Lenart, 1983). This assumption is