

A Simulation Model for Detecting Vessel Conflicts Within a Seaport

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ABSTRACT: Conflicts represent near misses between two moving vessels, and often occur in port waters due to limited sea space, high traffic movements, and complicated traffic regulations. Conflicts frequently result in congestion and safety concerns. If conflict risk can be predicted, one could take appropriate measures to resolve conflicts so as to avoid incidents/accidents and reduce potential delays. To the best of this researcher's knowledge, no systematic study has been carried out on the issue of detecting marine traffic conflicts. In this paper, we present an algorithm designed to determine a conflict using the criterion of vessel domain. The algorithm aims to evaluate the relative positions of vessel domains to detect potential conflicts. To implement the algorithm, a simulation model has been developed in Visual C++. The model at present provides a single function for conflict detection but can be expanded to a multi-functional system for resolving conflicts in future work.

1 INTRODUCTION

Traffic conflict refers to the event of vessel interference, which occurs in port waters due to the special characteristics of port traffic in limited sea space, high traffic density, and complex operational regulations. As undesirable incidents, conflicts have a direct effect on the safety of navigation. A conflict without proper resolution may lead to a collision resulting in a loss of life and property, and even threaten the ocean environment.

In recent years marine traffic has been increasing greatly due to the sustained growth of seaborne trade. As a result, the port traffic network becomes finely meshed and intensively used. The demand for the use of sea space sometimes exceeds the available capacity, such that even a small interaction (i.e. a conflict) between vessels may have a large impact on the entire network. The most common product of a conflict is time delay, which results from the evasive maneuvers of vessels to avoid a collision. Within a saturated network, these delays can slow the speed of traffic stream, increase vessel-waiting time

and the length of waiting queue. Traffic congestion would arise accordingly.

The world's busiest ports are faced with potential risk of traffic conflicts. However, maritime control centers often can only play an advisory role, which cannot satisfy the demand on traffic management arising within port waters. There is no positive control as to conflict avoidance.

If conflict risk could be predicted in advance, we could take appropriate measures to resolve or eliminate conflicts so as to avoid incidents/accidents and reduce the impact of conflict on network efficiency. However, to the best of this researcher's knowledge, no systematic method has been developed for detecting marine traffic conflicts. A review of past studies related to marine traffic safety revealed that almost all were focused on collision avoidance. Nevertheless, a conflict can be considered as a collision risk with a low degree of danger. Hence, works in collision avoidance are worth reviewing, which could provide valuable reference to this research.

Two criteria are used in past studies for determining a collision risk: the closest point of approach (CPA) and ship domain.

The criterion of CPA is applied with two parameters: distance of closest point of approach (D_{CPA}) and time of closest point of approach (T_{CPA}). The value of CPA parameters indicates the relative position between two vessels. For example, a smaller CPA indicates a higher risk of collision. The CPA parameters are applicable in a collision avoidance system, which can guide vessel to execute proper anti-collision maneuvers. An example is Lenart's studies (Lenart 1999, Lenart 2000) on what speed and/or course maneuver should be undertaken to achieve the required CPA time and distance.

The criterion of CPA is difficult to use in restricted waters such as narrow fairways. In view of this, the concept of ship domain has been proposed as a more comprehensive and accurate criterion. It can be explained as "a water area around a vessel which is needed to ensure the safety of navigation and to avoid collision" (Zhao et al. 1993). Vessel domain was first presented by Fujii et al. (1971). Based on field observations, Fujii's study established a domain model for a narrow channel. Later, Goodwin (1975) developed a domain model in open sea. Besides presenting a model, the study also analyzed how traffic density and length of vessel affect the size of vessel domain.

The shape and size of a vessel domain are affected by a number of factors (vessel's speed and length, sea area, traffic density etc.). As different factors are taken into account, ship domains proposed by various studies differ from one another. Many studies have focused on improving the vessel domain model (Davis et al. 1980, Coldwell 1983, Zhu et al. 2001, Pietrzykowski 2008).

In a port traffic system, vessels traveling along fairways are required to keep various safety clearances in accordance with the port's regulation. The domain of a vessel can thereby be referred to as the clearance area around it. This paper would attempt to design an algorithm to detect conflicts using the criterion of ship domain. That is, the relative positions of the domains of two vessels will be evaluated before they actually encounter each other. If the domain of a vessel will interfere with the domain of the other, a potential conflict is indicated.

A simulation model is developed to implement the algorithm, using Visual C++ 6.0. In the simulation model, conflicts can be detected for a given demand schedule of marine traffic within a seaport. The first and most important goal of conflict detection is to enable safe navigation and avoid collision between vessels. For system optimization, attention should also be paid to reduce the impact of conflicts

on network efficiency so as to improve traffic conditions within the seaport.

This paper is structured as follows: Section 1 introduces the issues addressed; Section 2 presents an overview of the simulation model; Section 3 describes the algorithm for conflict detection; Section 4 focuses on simulation model implementation; and Section 5 summarizes findings and proposes future work.

2 OVERVIEW OF SIMULATION MODEL

2.1 *The seaport traffic system*

A seaport traffic system can be treated as a network of nodes and links. Within the network each link indicates a section of a fairway, and a node can be a berthing/anchorage area, a boarding point for port pilots, an intersection area of fairways, or a separation point dividing a fairway into two sections due to differences in widths and/or traffic regulations. The route of a vessel can be represented by a path in the network consisting of a series of nodes and links.

Figure 1 shows a seaport traffic system we use in the simulation model, where black dots represent the nodes and a rectangle between two nodes indicates a link. The width of a rectangle indicates the width of the link. A vessel is only allowed to travel within the link.

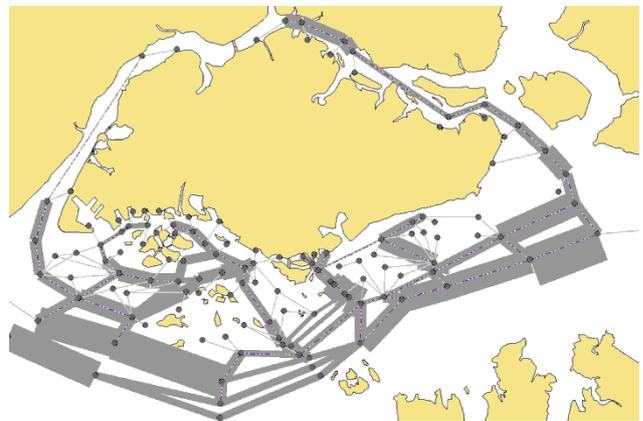


Figure 1. A seaport traffic system for Singapore.

2.2 *Flowchart for conflict prediction*

A seaport traffic system usually involves a large number of vessels. We need to detect a potential conflict between any pair of vessels. For any pair of vessels, the system will check whether they will conflict or not in a time interval (t_0, t_3).

There are two situations in conflict detection:

- Node conflict prediction: two vessels traveling toward the same node are on different links.
- Link conflict prediction: two vessels traveling toward the same node are on the same link.

In the first situation, the two vessels may have a conflict when they are passing the node. Thus, before the two vessels reach the node, the system needs to predict whether the two vessels will have a conflict.

In the second situation, the two vessels may encounter a conflict on the link. However, if the fairway is sufficiently wide so that a vessel can overtake the other safely, the conflict will not occur. Thus, the factor of the link width should be considered into conflict detection on a link. These are described in the next section.

Note that, the relative position between two vessels varies as vessels are moving. The conflict situation would change accordingly. Suppose that the vessels have a risk of conflict during a certain time period. According to the changes in vessel trajectories, this time period is divided into several time intervals. The system needs to separately evaluate the conflict situation during different time interval.

Figure 2 shows the flowchart for conflict detection (the notations t_0, t_1, t_2, t_3 are defined in Section 3).

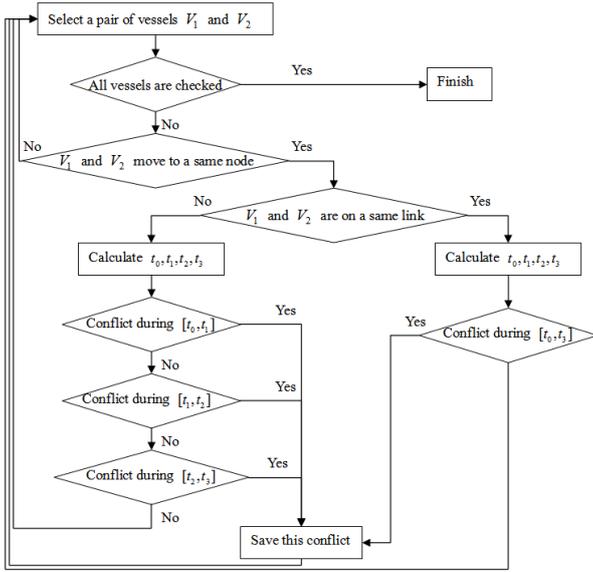


Figure 2. Flowchart for conflict prediction.

3 DETERMINE A CONFLICT BETWEEN TWO VESSELS

3.1 Preliminaries and assumptions

Denote a vessel as $V(O, d, \Phi, \Psi, \bar{\Phi}, \bar{\Psi}^1, \bar{\Psi}^2)$ as shown in Figure 3. For the purpose of simplifying analysis, a vessel is regarded as a rectangle V , whose dimensions are Φ (width) and Ψ (length). Suppose $O(x, y)$ is the center of the vessel. At present, it is travelling along the direction d .

The clearance area of a vessel is defined as a zone within which the vessel can keep enough distance to

avoid conflict with each other. The clearance area varies according to differences in a vessel's outline, dimension, technical parameters and fairway characteristics. In this research, the shape of a vessel's clearance area is assumed as a rectangle R . The parameter $\bar{\Phi}$ refers to the vessel's lateral clearance. Vessel's longitudinal clearance is represented by parameter $\bar{\Psi}^1$ in the direction of the bow and $\bar{\Psi}^2$ in the direction of the stern. The values of these parameters ($\bar{\Phi}, \bar{\Psi}^1, \bar{\Psi}^2$) are specified by regulation. These parameters can be set up in a simulation system as input data.

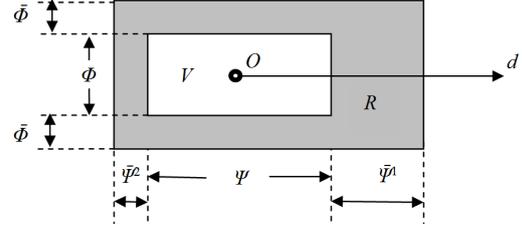


Figure 3. A vessel and its domain.

3.2 Node conflict prediction

Two vessels, V_1 and V_2 , on different links travel toward the same node. Table 1 lists the navigation information, where $t_1 < t_2$, i.e. V_1 will reach the node before V_2 .

Table 1. Two vessels on different links

	V_1	V_2
Position	A	E
Velocity before the node	\mathbf{v}_1	\mathbf{v}_2
Velocity after the node	$\bar{\mathbf{v}}_1$	$\bar{\mathbf{v}}_2$
Time to the node	t_1	t_2
Time to the next node	\bar{t}_1	\bar{t}_2

Suppose $t_0 = 0, t_3 = \min(\bar{t}_1, \bar{t}_2)$. We aim to check whether there is any conflict during the time interval $(0, t_3)$. The movements of V_1 with respect to V_2 are different in three different time intervals

- In the time interval (t_0, t_1) , the velocity of V_1 with respect to V_2 is $\mathbf{w}_1 = \mathbf{v}_1 - \mathbf{v}_2$.
- In the time interval $[t_1, t_2]$, the velocity of V_1 with respect to V_2 is $\mathbf{w}_2 = \bar{\mathbf{v}}_1 - \mathbf{v}_2$.
- In the time interval (t_2, t_3) , the velocity of V_1 with respect to V_2 is $\mathbf{w}_3 = \bar{\mathbf{v}}_1 - \bar{\mathbf{v}}_2$.

Figure 4 shows the movement of the center of V_1 with respect to the center of V_2 . With respect to V_2 , starting at A , V_1 passes B at t_1 , moves from B to C during $[t_1, t_2]$, and reaches D at t_3 . Thus,

$$AB = \mathbf{w}_1 t_1 = (\mathbf{v}_1 - \mathbf{v}_2) t_1,$$

$$BC = \mathbf{w}_2 (t_2 - t_1) = (\bar{\mathbf{v}}_1 - \mathbf{v}_2) (t_2 - t_1),$$

$$CD = \mathbf{w}_3 t_3 = (\bar{\mathbf{v}}_1 - \bar{\mathbf{v}}_2) t_3.$$

At location A , the domain of V_1 follows its moving direction \mathbf{v}_1 (Fig. 5(a)). Similarly, the domains of the vessels at different locations can be obtained (Table 2). Suppose $q_{ij}^5 = q_{ij}^1$, $i = 0, 1, j = 0, 1, 2, k = 1, 2, 3, 4$. Table 2 tells that

- Q_{ij}^k is a domain of the vessel V_i at $t = t_i$,
- q_{ij}^k is the k -th corner of the domain Q_{ij}^k ,
- $q_{ij}^k q_{i,j+1}^k$ is the k -th edge of the domain Q_{ij}^k .

The movement of the domain of V_1 with respect to the domain of V_2 is denoted as the relative movement of V_1 to V_2 . For example, referring to Figure 4, Figure 5 shows the relative movements of V_1 to V_2 , in the three different time intervals.

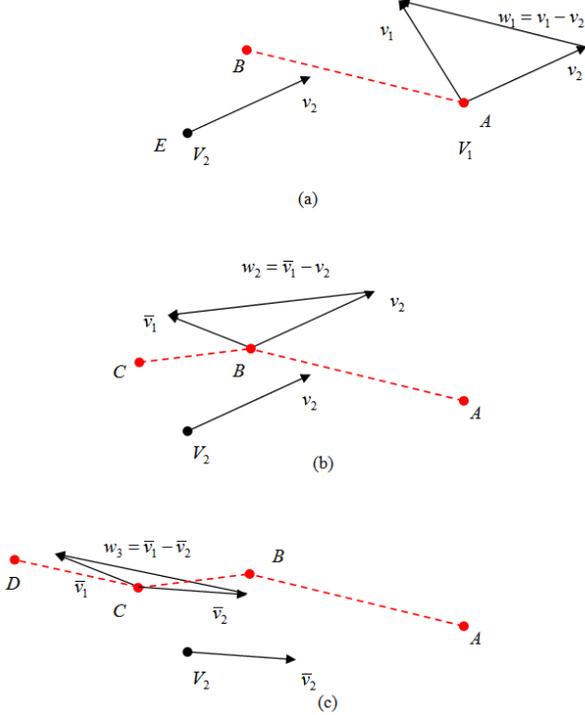


Figure 4. The movements of the center of V_1 with respect to the center of V_2 : (a) In time interval $(0, t_1)$; (b) In time interval $[t_1, t_2]$; (c) In time interval (t_2, t_3) .

Table 2. Domain of vessels at different locations

Location	Domain of V_1	Domain of V_2
$t=t_0$	$Q_{10}(q_{10}^1, q_{10}^2, q_{10}^3, q_{10}^4)$	$Q_{20}(q_{20}^1, q_{20}^2, q_{20}^3, q_{20}^4)$
$t=t_1$	$Q_{11}(q_{11}^1, q_{11}^2, q_{11}^3, q_{11}^4)$	$Q_{21}(q_{21}^1, q_{21}^2, q_{21}^3, q_{21}^4)$
$t=t_2$	$Q_{12}(q_{12}^1, q_{12}^2, q_{12}^3, q_{12}^4)$	$Q_{22}(q_{22}^1, q_{22}^2, q_{22}^3, q_{22}^4)$

For any $j=0, 1, 2$, in the time interval (t_j, t_{j+1}) , the velocity of V_1 with respect to V_2 is \mathbf{w}_{j+1} . The movement of the corner q_{ij}^k with respect to V_2 is a line segment $q_{ij}^k p_{ij}^k$ where

$$p_{ij}^k = q_{ij}^k + (t_{j+1} - t_j) \mathbf{w}_{j+1}.$$

Thus, the movement of the edge $q_i^k q_i^{k+1}$ with respect to V_2 is $P_j^k = q_i^k q_{i,j}^{k+1} p_{i,j}^{k+1} p_{i,j}^k$ (Fig. 6). If V_1 and V_2 conflict with each other, the movement of at least one edge of V_1 will intersect with the domain of V_2 , i.e.

$$P_j^k \cap Q_{2j} \neq \emptyset.$$

Figure 6 shows an example when there is no conflict between V_1 and V_2 . Figure 7 is another example when there is a conflict between V_1 and V_2 .

In summary, V_1 and V_2 will conflict in the time interval (t_j, t_{j+1}) if and only if

$$U(P_j^k \cap Q_{2j}) \neq \emptyset.$$

In this way, the conflict detection turns to checking whether two parallelograms intersect with each other or not.

3.3 Link conflict prediction

Suppose a vessel V_1 follows another vessel V_2 along a link (see Fig. 8(a)). Table 3 lists the navigation information of these vessels. The velocity of V_1 with respect to V_2 is

$$\mathbf{w}_1 = \mathbf{v}_1 - \mathbf{v}_2.$$

If \mathbf{v}_1 is not larger than \mathbf{v}_2 , V_1 and V_2 will conflict if and only if

$$|AE| < \frac{L_1 + L_2}{2}.$$

Suppose $t_3 = \min(t_1, t_2)$. We need to check whether the two vessels will conflict with each other during $(0, t_3)$. After that, the two vessels will not be conflicting on the link, because one vessel leaves this link. If \mathbf{v}_1 is larger than \mathbf{v}_2 , during $(0, t_3)$, the relative movement of V_1 with respect to V_2 is shown in Figure 8(b), where

$$p_1^k = q_1^k + \mathbf{w}_1 \times t_3, \quad k = 1, 2, 3, 4.$$

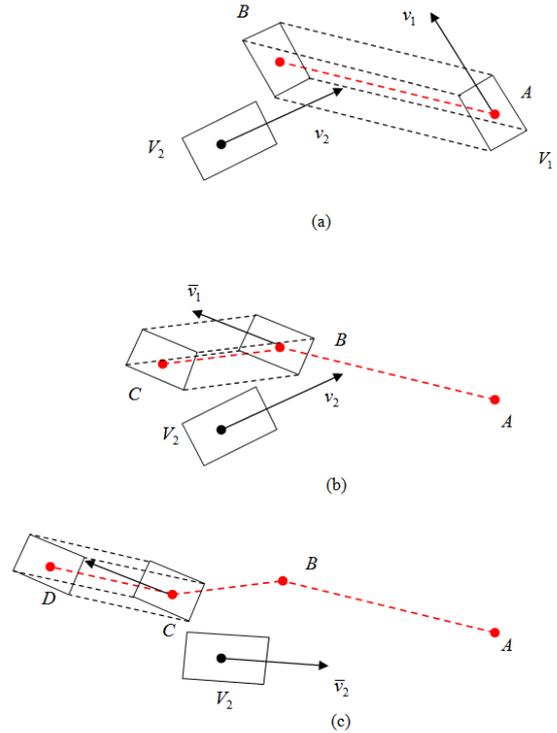


Figure 5. The relative movement of V_1 to V_2 : (a) In time interval $(0, t_1)$; (b) In time interval $[t_1, t_2]$; (c) In time interval (t_2, t_3) .

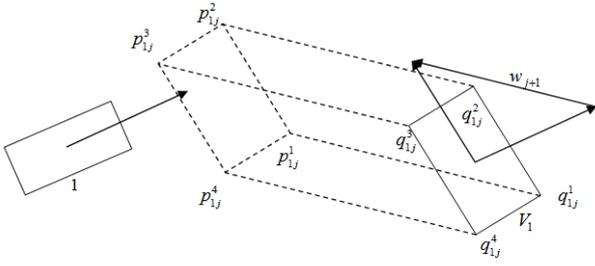


Figure 6. $P_j^k \cap Q_{2j} \neq \emptyset$, V_1 and V_2 will not conflict with each other in the time interval (t_j, t_{j+1}) .

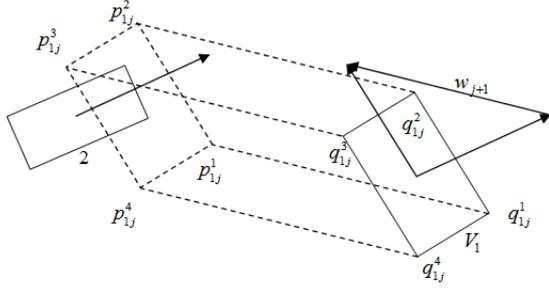


Figure 7. $P_j^2 \cap Q_{2j} \neq \emptyset$, $P_j^3 \cap Q_{2j} \neq \emptyset$, V_1 and V_2 will conflict with each other in the time interval (t_j, t_{j+1}) .

Obviously, V_1 and V_2 will have a conflict if and only if $q_1^1 q_1^4 p_1^2 p_1^3$ intersects with Q_2 . In Figure 9(a), $q_1^1 q_1^4 p_1^2 p_1^3$ intersects with Q_2 , thus V_1 and V_2 are in conflict. In Figure 9(b), $q_1^1 q_1^4 p_1^2 p_1^3$ does not intersect with Q_2 , thus V_1 and V_2 will not conflict with each other.

The conflict detection method described earlier is merely based on an assessment of relative movement of one vessel to another vessel. The system judges if a conflict will occur by checking whether the two parallelograms intersect. If link width is taken into consideration, the result may be different. Suppose the width of the link is W , and the width of the domains of the two vessels are W_1 and W_2 . The two vessels can travel in parallel without a conflict if the width of the link is not smaller than the sum of W_1 and W_2 (Fig. 10).

Table 3. Two vessels on different links

	V_1	V_2
Position	A	E
Velocity	v_1	v_2
Domain	$Q_1 (q_1^1, q_1^2, q_1^3, q_1^4)$	$Q_2 (q_2^1, q_2^2, q_2^3, q_2^4)$
Domain length	L_1	L_2
Domain width	W_1	W_2
Time to leave	t_1	t_2

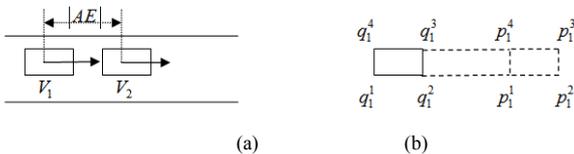


Figure 8. Vessels on the same link.

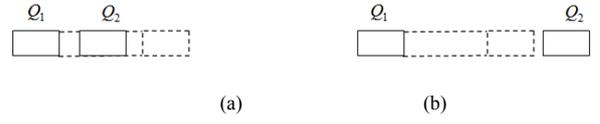


Figure 9. Vessel conflict on the same link depends on initial vessel positions

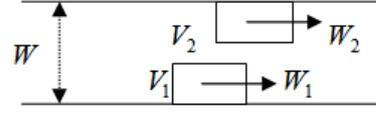


Figure 10. Vessels travel in parallel on a link

4 EXAMPLES AND DISCUSSIONS

We have implemented the conflict detection algorithm in the simulation model using Visual C++ 6.0 on a Windows XP operating system. In this section, some examples are shown to illustrate the results of our algorithm.

Figure 11 is the first example. Two vessels travel toward the same node. A vessel is represented as a rectangle with a solid line indicating the travelling direction. The vessel on the left hand side is V_1 and the other one is V_2 . The gray areas in Figure 11(a) indicate the link areas. At any time, a vessel keeps inside a link area. The gray areas in Figure 11(b), enclosed by solid lines, indicate the relative movement of V_1 to V_2 . A conflict is predicted since the relative movement intersects with the domain of V_2 (Fig. 11(b)). Figure 11(e) shows that the two vessels conflict with each other when they are passing the node.

The result also shows that the conflict can be predicted at any time before the conflict time. Figure 11(b) and Figure 11(d) show the relative movements of V_1 to V_2 at different positions. As we can see from the figure, the same conflict is predicted in both positions. In fact, the conflict prediction algorithm will detect the conflict any time before either vessel reaches the node. The result implies that we can increase the simulation time interval, thus reduce the calculation for conflict detection.

Figure 12 is an example with two vessels travelling on the same link. The vessel V_1 tries to catch up with V_2 . The gray area enclosed by black lines in Figure 12(b) is the relative movement of V_1 to V_2 . Combining Figure 12(a) and Figure 12(b), we know that this relative movement intersects with the domain of V_2 . Thus V_1 will catch up with V_2 . If the link width is not enough, V_1 and V_2 will come into conflict (Fig. 12(c)). On the other hand, if the link width is enough for the two vessels to navigate in parallel, there will be no conflict (Fig. 13).

In Figure 13(a), two vessels in parallel will not conflict with each other, because the relative movement of V_1 to V_2 does not intersect with the domain of V_2 . Therefore, V_1 can catch up with V_2 and overtake it.

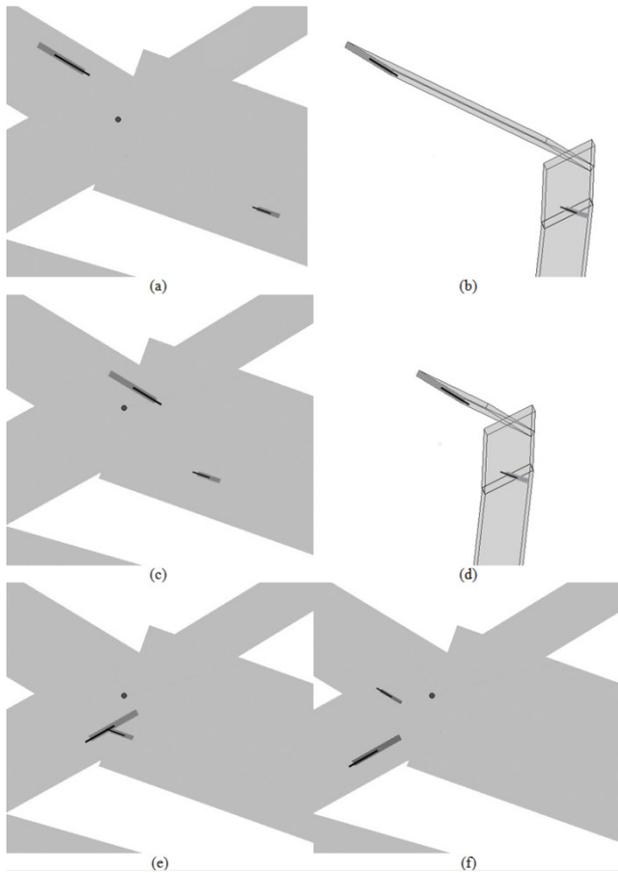


Figure 11. Two vessels from different links conflicting each other at a node

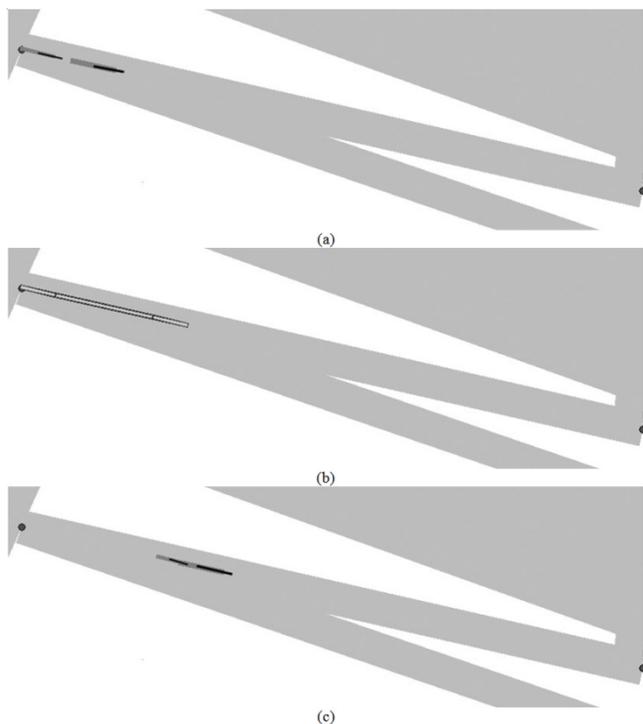


Figure 12. Two vessels on the same link in conflict

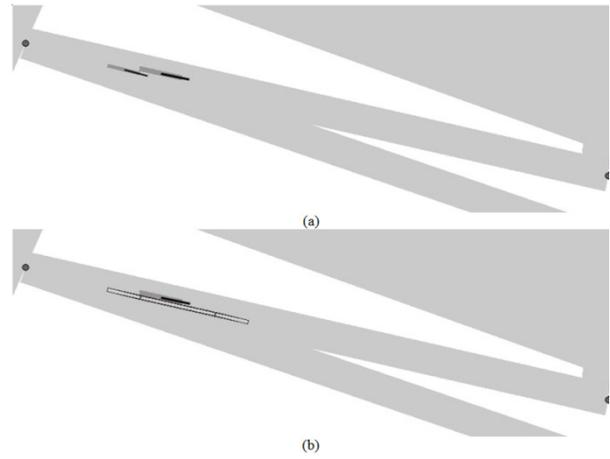


Figure 13. Two vessels on the same link travel in parallel.

5 SUMMARY AND CONCLUSIONS

A simulation model has been developed for predicting potential vessel conflicts within a seaport. An algorithm for conflict detection was designed with the use of ship domain criterion: when the relative movement of one vessel with respect to a second vessel intersects with the domain of the second vessel, the two vessels will have a conflict. The algorithm simplifies the conflict detection problem by checking whether two parallelograms intersect with each other.

An application of the model was demonstrated using the seaport of Singapore as an example. Inputs to the model include the background map, data on fairways, and information on vessel types and characteristics. Vessel arrivals and vessel routes are generated by the model according to statistical distributions. Simulation results showed that conflicts can be accurately predicted in time. The logic of conflict detection is applicable to other traffic systems by changing the input data. Thus, the simulation model is a generic model which can be adapted to other busy seaports that are faced with traffic congestion and delays.

For future work, human factor could be taken into account. Human error would affect vessel movement as well as conflict situation. An example is the situation where one vessel follows another vessel along a link. Even with sufficient width for overtaking, an accident/ incident may occur as a result of human error. Another possible improvement will focus on the determination of a reasonable time step in simulation. In the current system, a single conflict may be detected for multiple times. When the time step is too small, a conflict may be predicted many times. On the other hand, if it is too large, some conflicts may not be detected. Thus, the determination of an optimum simulation time step is also an important issue.

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