MODELING COLLISION AVOIDANCE DECISIONS IN NAVIGATION

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Abstract: Due to grave potential human, environmental and economical consequences of collisions at sea, collision avoidance has become an important safety concern in navigation. To reduce the risk of collisions at sea, appropriate collision avoidance actions need to be taken in accordance with the regulations, i.e., International Regulations for Preventing Collisions at Sea. However, the regulations only provide qualitative rules and guidelines, and therefore it requires navigators to decide on collision avoidance actions quantitatively by using their judgments which often leads to making errors in navigation. To better help navigators in collision avoidance, this paper develops a comprehensive collision avoidance decision making model for providing whether a collision avoidance action is required, when to take action and what action to be taken. The model is developed based on three types of collision avoidance actions, such as course change only, speed change only, and a combination of both. The model has potential to reduce the chance of making human error in navigation by assisting navigators in decision making on collision avoidance actions.

1 INTRODUCTION

Due to grave potential human, environmental and economical consequences of collisions at sea, collision avoidance has become an important safety concern in navigation. The growth of shipping traffic over the past decades [1] and the increase in ship sizes [2] are likely to result in more traffic movements [3], especially in restricted waters, consequently increasing the risk of collisions.

Human error has been identified as one of the leading factors to cause maritime accidents. According to [4], about 89-96% of collisions are caused by some form of human error. Navigation is a laborious, complicated and error-prone process [5]. When it is coupled with high fatigue, stress and work pressure, making error in taking collision avoidance actions is likely for navigators.

To reduce the risk of collisions, appropriate collision avoidance actions should be taken in accordance with the International Regulations for Preventing Collisions at Sea (COLREGs) [6]. The COLREGs only provide qualitative rules and guidelines on actions. However, in order to decide and implement an action, it needs to be quantitatively defined (e.g., amount of rate of turning, amount of speed change). Navigators decide on the actions based on their knowledge, experience and technical ability, along with the COLREGs. While taking actions, navigators often violate the COLREGs through mutual understanding between the crews of interacting vessels. However, this contravention has been identified as one of main factors contributing to collisions [7]. Therefore, to help ship navigators in collision avoidance and reduce human error, a decision making model is required to provide quantitative maneuvering suggestions based on the COLREGs.

Facilitating collision avoidance by providing maneuvering suggestions has attracted attentions from different researchers. Coenen et al. [8] developed a knowledge-based collision avoidance system. This system utilizes expert's knowledge to qualitatively decide on collision avoidance actions, which are further quantitatively determined yet restricted to limited and discrete values. Using kinematic information, Kwik [9] developed a model to calculate the time at which a collision avoidance action should be initiated. This model is limited
to the action of changing course only. However, according to the COLREGs rule 8(b), collision avoidance actions can be changing course, changing speed or both together. Therefore, it is necessary to consider the three types of actions, and quantitatively determine continuous values of the actions, in developing models for collision avoidance decision making.

This paper develops a comprehensive collision avoidance decision making model, which decides 1) whether a collision avoidance action is required, 2) when to take action and 3) what action to be taken. By using kinematic information, this model provides manoeuvring suggestions on actions, which are quantitative in nature.

In the rest of the paper, the concept of the collision avoidance decision making model is discussed in Section 2, followed by the mathematical model for computing when to take action and what action to be taken. The model is illustrated for three types of collision avoidance actions in Section 3, before providing conclusions in Section 4.

2 METHODOLOGY

2.1 Collision Avoidance Decision Making Model

A Collision avoidance decision making model utilizes vessel kinematic information to decide on the three fundamental questions in collision avoidance

1) Whether to take action?
2) When to take action?
3) What action to be taken?

The developed model in this paper, as shown in Fig. 1, addresses the three questions through a process of data collection, preliminary assessment of the necessity of actions, and quantitative determination of actions. The process is discussed in the subsequent sections.

Data Collection; Collection of static and dynamic navigational data is the first step of collision avoidance decision making. Besides visual observations, navigational aids, such as Automatic Radar Plotting Aid (ARPA), Electronic Chart Display and Information System (ECDIS), and Automatic Identification System (AIS) can provide the required navigational data. These data embrace vessel's information including structural attributes, position, course, speed, and environmental information including wave, current, wind, etc, which are necessary for a navigator to perceive risk of collisions and to compute necessary actions by using the model.

Fig. 1 Block diagram for collision avoidance decision making model

Whether to Take Action; In order to decide on whether a collision avoidance action is required, a three step procedure is formulated. In the first step, based on trajectory data, target ships (TS) can be identified as the ships approaching the ship domain (SD) or plying within the SD of the own ship (OS). The SD is defined as the surrounding effective waters which the navigator of ship wants to keep clear of other ships of fixed objects [10]. In the second step, the existence of collision risk is determined based on the values of the Distance at the Closest Point of Approach (DCPA) and the Desired Passing Distance (DPD). The DPD is the safe distance to pass a TS which is perceived by the navigator of the OS. If the DCPA is less
than the DPD, collision risk exists for the TS. Therefore, taking an avoidance action is necessary. On the other hand, if the DCPA is greater than the DPD, no action is necessary as no collision risk exists. The final step is to determine the operational responsibility of actions according to the COLREGs. The navigators on the give-way ship need to consider when to take action and what action to be taken. For the stand-on ship, the navigators need to maintain a proper look-out on the give-way ship to check whether it has taken any action. When collisions cannot be avoided by the give-way ship alone, navigators on stand-on ship need to consider taking actions. Based on abovementioned three steps, ship navigators can decide whether to take collision avoidance actions.

When to Take Action and What Action to be Taken; The decisions of collision avoidance in navigation include two important coherent outputs: when to take action and what action to be taken. In addition, the goal of collision avoidance actions is to achieve the preset DPD. Therefore, three governing conditions (DPD, when to take action, what action to be taken) together form collision avoidance decisions. By limiting any two of the three conditions, the remaining one can be numerically computed which will be addressed in the Section 2.2.

Though DPD is decided by ship navigators, it also depends on numerous factors, including the encounter situation and traffic density [11], navigable sea room [12], ship specifications [13, 14], weather condition and visibility [12], etc. Therefore, the effect of those elements to collision avoidance decisions can be considered in the determination of DPD.

In the model, the time to take action is measured by the time-to-last-minute-action \( T_{limu} \) which is defined as the remaining time for the ship navigator to execute the last extreme collision avoidance action, e.g. the maximum Rate of turn (ROT) in order to achieve a DPD from other ships. Therefore, the \( T_{limu} \) is a time buffer which suggests navigators how long they can remain watching the situation and planning for maneuvers without taking any action. Furthermore, it sets a deadline for the stand-on ship when potential violations of the desired passing distance cannot be avoided by the give-way ship alone. In such cases, the stand-on ship needs to consider collision avoidance actions.

The possible collision avoidance actions considered in this model include three categories

1) Course change
2) Speed change
3) Course change and speed change

The comprehensive actions of course change and speed change necessitate considerations especially when risk of collisions become fairly critical, e.g., in near-miss or close-quarter situations.

Implementation of Collision Avoidance Actions; After determining when to take action and what actions to be taken, navigators execute a rudder angle and/or propeller revolution to mitigate the risk of collision. After taking actions, navigators on both of the OS and TS still need to check the effectiveness of the actions and remain alert until the two ships pass each other without violation of the DPD. If it is projected that DPD will still be violated after the previous actions, additional collision avoidance actions need to be considered by navigators on both of the involved ships.

2.2 Model Formulation

In this section, the mathematical model for computing when to take action and what action to be taken will be addressed. The model is based on a principle assumption that when the OS is executing collision avoidance actions, the TS will keep its course and speed constant. Moreover, if the action of course change is chosen, the ship will proceed along circular paths with preselected turning radius. From the model, the \( T_{limu} \) is computed by assigning values to DPD, maximum ROT and maximum deceleration. In addition, the required ROT and deceleration can be computed for each time point in the decision making process for a given value of DPD.

Computing Time-to-Last-Minute-Action; Let a crossing encounter in which the OS is the give-way ship and TS is the stand-on ship, as shown in Fig. 2, with an x-y coordinate system always attached to the OS. At the start time, the x-axis is in the direction of the velocity of OS, and the y-axis is perpendicular to it and positive to starboard.
Given an initial state, the $T_{tma}$ can be expressed as a function of following variables:

$$T_{tma} = f(x_r^0, y_r^0, \phi_r^0, v_o, v_o, R_o, a, m_c)$$

(1)

where

- $x_r^0, y_r^0$ the relative coordinates of the TS’s position with respect to OS at the start time,
- $\phi_r^0$ the relative heading of TS to OS at the start time,
- $v_o, v_o$ the speeds of OS and TS at the start time,
- $R_o$ the turning radius,
- $a$ the acceleration of OS,
- $m_c$ the desired passing distance.

![Collision avoidance actions in a crossing encounter](image)

In the course-changing phase, the TS still follows the straight line with the original constant speed, and the OS make a circular turn. Then the relative state variables of TS’s position to OS in the final situation can be derived as

$$x_f^r = x_r^a + v_o T_2 \cos \phi_o^a - R_o \sin \left( \frac{v_o T_2 + 0.5a T_2^2}{R_o} \right)$$

(5)

$$y_f^r = y_r^a + v_o T_2 \sin \phi_o^a - R_o \cos \left( \frac{v_o T_2 + 0.5a T_2^2}{R_o} \right)$$

(6)

$$\phi_f^r = \phi_o^a - \frac{v_o T_2 + 0.5a T_2^2}{R_o}$$

(7)

$$\phi_f^o = \phi_o^a - v_o T_2 + 0.5a T_2^2$$

(8)

$$v_f^r = \frac{v_o T_2 + 0.5a T_2^2}{R_o}$$

(9)

$$v_f^o = v_o + a T_2$$

(10)

where,

- $x_f^r, y_f^r$ the relative coordinates of the TS’s position to OS in the final situation,
- $\phi_f^r$ the relative heading of TS to OS in the final situation,
- $\phi_f^o, \phi_o^f$ the heading of OS and TS in the final situation,
- $v_f^r$ the speed of OS in the final situation,
- $T_2$ the period in the course-changing phase.

In the final situation, the collision risk measures, TCPA and DCPA can be derived as

$$TCPA = \left[ \left[ \frac{\left[ v_o \cos \phi_f^r - v_o \cos \phi_f^o \right]}{v_o \cos \phi_f^r - v_o \cos \phi_f^o} \right] + \left[ \frac{\left[ v_o \sin \phi_f^r - v_o \sin \phi_f^o \right]}{v_o \sin \phi_f^r - v_o \sin \phi_f^o} \right] \right]^{1/2}$$

(11)

$$DCPA = \left[ \left[ \frac{\left[ v_f^r \cos \phi_f^r - v_f^o \cos \phi_f^o \right]}{v_f^r \cos \phi_f^r - v_f^o \cos \phi_f^o} \right] + \left[ \frac{\left[ v_f^r \sin \phi_f^r - v_f^o \sin \phi_f^o \right]}{v_f^r \sin \phi_f^r - v_f^o \sin \phi_f^o} \right] \right]^{1/2}$$

(12)

By assigning $DCPA = m_c$ and $TCPA = 0$, another set of $x_a$ and $y_a$ at the action point can be computed as

$$y_r^a = y_r^0 + v_o T_1 \sin \phi_r^0$$

(3)

$$\phi_r^a = \phi_r^0$$

(4)
\[ x_r^0 = \pm m_r \left\{ \begin{array}{c} v_x \cos \phi^0_r - (v_r + a_T) \cos \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \\ v_x \sin \phi^0_r - (v_r + a_T) \sin \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \end{array} \right\}^{1/2} \]

\[ -v_r T_z \cos \phi^0_r + R_o \sin \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \] (13)

\[ y_r^0 = \pm m_r \left\{ \begin{array}{c} v_x \sin \phi^0_r - (v_r + a_T) \sin \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \\ v_x \cos \phi^0_r - (v_r + a_T) \cos \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \end{array} \right\}^{1/2} \]

\[ -v_r T_z \sin \phi^0_r + R_o \left( 1 - \cos \left( \frac{v_r T_z + 0.5a_T T_z^2}{R_o} \right) \right) \] (14)

By substituting \( T_{\text{lma}} \) for \( T_1 \), the \( x_r^a \) and \( y_r^a \) in equation (1) and (2) are expressed as

\[ x_r^a = x_r^0 + v_r T_{\text{lma}} \cos \phi^0_r - v_r T_{\text{lma}} \]

\[ y_r^a = y_r^0 + v_r T_{\text{lma}} \sin \phi^0_r \] (15)

By equating (13) and (15), (14) and (16) respectively, two equations with two unknown variable \( T_z \) and \( T_{\text{lma}} \) can be obtained. By solving the simultaneous equations, the \( T_{\text{lma}} \) can be finally extracted.

Computing Required Collision Avoidance Actions; According to equation (1), by assigning a value to \( T_{\text{lma}} \), a set of required turning radii and decelerations can be further determined for each time point. In particular, if only one choice of action e.g. the course change is considered, the acceleration/deceleration needs to be set to 0. Then from the model, the required Rate of Turn (\( ROT = \frac{v_r}{R_o} \)) can be determined uniquely for each time point. It is similar to the case in which only speed change is considered. Illustration of these three types of collision avoidance actions will be given in the subsequent section.

3 MODEL ILLUSTRATION

In order to illustrate the application of the model, a two-ship crossing encounter is designed with the parameters and collision risk measures listed in Table 1 and Table 2. At the start time, since the DCPA (0.2 n.m.) is less than the DPD (0.7 n.m.), collision avoidance actions are required. According to the initial relative position of TS to OS, the OS is identified as the give-way ship and is responsible to take collision avoidance action. The three types of collision avoidance actions will be discussed consecutively as follows.

Table 1. Parameters of illustration at the start time

<table>
<thead>
<tr>
<th>Ship</th>
<th>Speed [knots]</th>
<th>Course [degrees]</th>
<th>Position coordinates x [n.m.]</th>
<th>y [n.m.]</th>
<th>DPD [n.m.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>15</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>TS</td>
<td>10</td>
<td>250</td>
<td>2.8</td>
<td>1.2</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 2. Collision risk measures

<table>
<thead>
<tr>
<th>Risk measures</th>
<th>DCPA [n.m.]</th>
<th>TCPA [min]</th>
<th>Range [n.m.]</th>
<th>Range Rate [knots]</th>
</tr>
</thead>
<tbody>
<tr>
<td>values</td>
<td>0.20</td>
<td>8.19</td>
<td>3.046</td>
<td>-20.6</td>
</tr>
</tbody>
</table>

3.1 Action of course change only

In this illustration, the action of course change only is considered. Therefore, in the equations formulated in Section 2.2, all the accelerations are assigned to 0. Given a maximum ROT (35.2 deg/min) or a minimum turning radius (0.4 n.m.), the required ROT can be computed with respect to each time-to-last-minute-turning (\( T_{\text{lma}} \)) shown in Fig. 3.

![Fig. 3 The relationship between the required ROT and \( T_{\text{lma}} \)](image_url)

From Fig.3, it can be noticed that with the same reduction of 0.5 min in the \( T_{\text{lma}} \), the increase in the required ROT is much greater when \( T_{\text{lma}} \) is around 1 min than that when \( T_{\text{lma}} \) is around 3 min. It can be interpreted that as the \( T_{\text{lma}} \) decreases i.e., as the ship approaches to the point where the extreme action should be taken, the marginal required ROT increases. Therefore, the
marginal difficulty of making a turn gets greater as $T_{lmd}$ decreases. In this regard, the measure of the $T_{lmd}$ may be useful to warn ship navigator against very late action.

Suppose the OS starts turning at the time $T_{lmd} = 3.5$ min, then the required ROT is approximately 6.28 deg/min with the corresponding turning radius of 2.28 n.m. The trajectories of OS and TS are plotted in Fig. 4 in which a course changing is executed for collision avoidance in the crossing encounter.

![Fig. 4](image)

Fig. 4  The ship trajectories in course change process

3.2 Action of speed change only

When only the action of speed change is considered, the ROT needs to equal 0. This can be approximately achieved by assigning a large value to the turning radius. In this illustration, a maximum deceleration (0.085 ft/sec$^2$) has been assumed. Then from the model, in order to achieve the DPD (0.7 n.m.), the required decelerations can be computed for each time point measured by the time-to-last-minute-deceleration ($T_{lmd}$) in Fig. 5.

From Fig. 5, the marginal required deceleration is also increasing as the vessel approaches to the point where extreme deceleration needs to be executed. However, by contrast to the marginal required ROT in the previous illustration, the rate of increment in the marginal required deceleration is less. Therefore, as the give-way ship approaches to the last minute action point, the increase in the marginal difficulty of speed change is less than that of course change.

![Fig. 5](image)

Fig. 5  The relationship between the required acceleration and $T_{lmd}$

Suppose, the OS starts the action of speed reduction at the time when $T_{lmd} = 3.5$ min, then the required deceleration reaches -0.036 ft/sec$^2$. Fig. 6 shows the corresponding trajectories of OS and TS when the speed reduction is executed.

![Fig. 6](image)

Fig. 6  The ship trajectories in speed reduction process

3.3 Combined action of course change and speed change

When combined actions of course change and speed change are simultaneously considered as collision avoidance actions, pairs of required ROT and deceleration can be obtained in Fig 7. In this illustration, a maximum ROT (35.2 deg/min) or minimum turning radius (0.4 n.m.) and a maximum deceleration (-0.085 ft/sec$^2$) are
assumed. Then, the required ROTs and decelerations can be computed for each time point measured by the time-to-last-minute-turning & deceleration ($T_{lmtd}$).

![Graph showing the relationship between required ROT and deceleration $T_{lmtd}$](image)

**Fig. 7** The relationship between the required ROT and deceleration $T_{lmtd}$

Assume a ship navigator executes the action at $T_{lmtd} = 3.5$ min, one pair of the corresponding required ROT equals 6.28 deg/min or the turning radius equals 2.28 n.m., and the required deceleration equals -0.01 ft/sec$^2$. The trajectories of the two ships along the collision avoidance process are shown in Fig. 8.

![Graph showing ship trajectories](image)

**Fig. 8** The ship trajectories in course change and speed reduction process

### 4 CONCLUSIONS

In this paper a comprehensive collision avoidance decision making model has been developed. When risk of collisions is identified, the model provides manoeuvring suggestions to ship navigators about whether a collision avoidance action is required, when to take action and what action to be taken. A new measure, time-to-last-minute-action has been proposed to represent the time when an action is initiated. The model has considered three types of actions including course change, speed change and a combination of these two. To illustrate the model, the three types of actions have been considered for collision avoidance in a crossing encounter. This collision avoidance decision making model has potential to ease navigators’ fatigue, stress and work pressure by facilitating decision making on collision avoidance actions, and consequently could reduce the likelihood of human errors in navigation.

### REFERENCES


AUTHOR’S BIOGRAPHY

Wang Yue Ying is currently a PhD student at National University of Singapore, Department of Civil Engineering. She received a BEng in Civil Engineering from Dalian University of Technology, China in 2008. Her research activities currently focus on safety studies of maritime transportation, including collision risk management, modeling collision avoidance decision making in maritime navigation.