Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2016, 45 (117), 88–93
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/090

Received: *31.08.2015*
Accepted: *18.12.2015*
Published: *25.03.2016*

The area-dynamic approach to the assessment of the risks of ship collision in the restricted water

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Key words: risk assessment, ship's domain, risk index, scale of risk, ship collisions, restricted water

Abstract

In this paper, two indexes for own ship risk collision assessment in the restricted water are proposed. The first one concerns the collision threats for ships. The second one describes threats that are generated by human error. It is carried out dynamically with accordance to changes in time. To realize the main aim of the paper, the definition of the extended domain of the ship is introduced. Furthermore, the rules to determine the indexes and range of their values are developed. Finally, a comprehensive model and its potential application are presented. There are some important things to take into account during the model development: the interface, the levels and type of the output information, the type and accuracy of the information about the position and movement dynamics of the particular ships. It gives the opportunity to consider the different operation levels. In addition, it also allows us to take into account the different levels of measurement and the collision risk warnings. This approach can be helpful for both the VTS operator and OOW, the ship's navigator, as the tool to support the safe navigation in restricted water.

Introduction

Safe operation of the ship requires constant analysis and evaluation of the situation. On this basis the navigator undertakes decisions concerning navigation. The analysis and assessment of the situation are carried out in accordance with the criteria adopted by the navigator. A commonly used criterion in collision avoidance systems is the closest point of approach. However, in most cases of navigation in restricted waters, particularly in narrow fairways and channels, this is difficult to apply. This is due to the lack of free choice of route and the need for compliance with safety rules and taking into account the local conditions (restriction of one of the three dimensions defining the distance of the ship from other objects) (Wielgosz & Pietrzykowski, 2012).

An alternative to the mentioned criterion of the navigational safety is the criterion of the ship domain. Application of the criterion of ship domain enables quick identification and assessment of the navigational situation and thus developing the decision support in the ship's manoeuvre (Rutkowski, 1998; Pietrzykowski, 2004). It should be noted that this criterion is also possible to use in the open sea areas (Pietrzykowski, Magaj & Chomski, 2009).

The safety level is most often determined by risk measure. There are many ways of defining the risk. Generally it is identified with possible effect (losses) of an unwanted event (accident).

A more exact definition says that it is the probability of losses due to an accident, which may arise in a particular part of the man-technique-environment system. In practice it means the necessity of mailing the conception of risk reduction measures and calculating the risk reduction achieved and the associated value of losses. In the maritime transportation system the main goal is to reduce the ship collision risk or navigational risk (Galor, 2009). The assessment of the risks of ship collision applied in this paper is based on a concept of a ship domain, which according to definition given by (Goodwin, 1975), is the area around the vessel which the navigator would like to keep free of other vessels, for safety reasons.

Since the first introduction of the ship domain concept by (Fujii & Tanaka, 1971), various researchers have attempted to quantify the size of this domain. It is clear that the basic problem is to define the domain boundary, dividing the area around the ship into sub-areas: dangerous and safe. It is a difficult task because the shape and size of the domain are affected by many factors. These include: size and manoeuvrability of the vessel, parameters of the area where the ship manoeuvres, hydro-meteorological conditions, vessel speed and the speed of other vessels, the intensity of vessel traffic in the area, the accuracy of position fixing, training level and knowledge and experience of navigators. Also significant is the adopted method of determining the ship domain boundary. Moreover, the sizes of the domains proposed in the literature vary quite significantly (Jingsong, Zhaolin & Fengchen, 1993; Wang et al., 2009).

The issue of determining the domain was presented in many publications, including (Fuji & Tanaka, 1971; Goodwin, 1975; Coldwell, 1983; Zhao, Wu & Wang, 1993; Śmierzchalski & Weintrit, 1999; Pietrzykowski, 2008; Pietrzykowski & Uriasz, 2009; Wang et al., 2009; Szłapczyński & Szłapczyńska, 2015).

Domains can be classified by their shape: circular, elliptical and polygonal domains. In the case of three-dimensional domains – they also describe vertical space included between the ship and the sea bottom and the air draft of the ship. Their shape often corresponds to sphere, ellipsoid, cylinder or truncated cone. A distinction can also be made between fuzzy domains and crisp domains. Fuzzy domains such as that proposed by (Pietrzykowski, 2008; Wang et al., 2009) seem preferable in terms of the safety analysis of marine traffic, but are at present still under development. Crisp domains use a simple classification of a situation between safe or unsafe, which evidently is a simplification.

Ship Risk Index

The concept of the ship risk index is proposed as the extension of the ship domain. As mentioned in Section 1, it is assumed that the domain is an area (domain two-dimensional) or space (three-dimensional domain) around the vessel which should be kept clear of other objects. Thus, the domain can be defined as an ellipse with the major axis along the ship's length (LOA) and the minor axis perpendicular to the ship's beam, as illustrated in Figure 1. The half-length of the major axis is taken as 4 LOA while the half-length of the minor axis is taken as 1.6 LOA. A number of comments should be made in the use of this domain (Montewka et al., 2011):

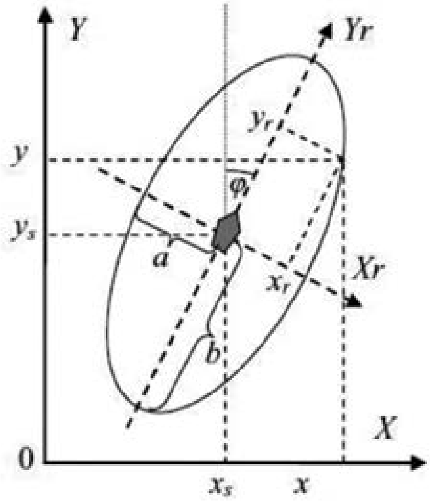

Figure 1. The sample of ship domain, with the following axes: *a* = 1.6 LOA, *b* = 4 LOA (Wang et al., 2009)

- the domain is symmetric, which implies that the possible influence of the COLREGs is not taken into account;
- another consequence of this symmetry is the fact that passing behind the stern is considered as dangerous as passing in front of the bow;
- in the meeting between ships, the largest ship has the largest domain; this means that for the largest vessel, the situation is classified as dangerous, whereas for the smallest vessel, the situation may still be evaluated as safe;
- the domain is affected by ship length only, neither ship type nor hydro meteorological conditions are included in the analysis.

However the latter can be supported by recent research, which revealed that the ship domain has a relatively low correlation with the sea state and wind force (Kao et al., 2007).

Among the methods of determining the ship domain one can distinguish three groups: statistical methods, analytical methods and artificial intelligence methods. It is characteristic for all these methods that they make use of the navigator's knowledge, both procedural and declarative.

Application of statistical methods requires the registration of relevant data. The problems that arise are separating the various factors that influence the shape and size of the domain and difficulties in collecting the data.

Analytical methods are based on the analytical description of the domain space. These methods ensure precise description of the ship domain. The main difficulty is to take into account and balance all relevant factors affecting the shape and size of the domain.

Methods of artificial intelligence (AI) were developed to acquire and use the knowledge of expert navigators using the tools of artificial intelligence. They include and use, *inter alia*, fuzzy logic, artificial neural networks and evolutionary algorithms.

Thus, the authors propose the approach that the ship can be described by two indexes $r_g(t)$ – the scale of the risk generated by their own ship and $r_e(t)$ – the scale of the exposure risk of their own ship as the mixture/combination of the statistical and analytical methods.

According to the ships domain description, we assume that these indexes are dependent on:
- type of vessel;
- distance to the potential place of collision (CPA, TCPA);
- basic ship operation data (velocity, position, course);
- visibility;
- number of ships in the area (vessel traffic flow); ship traffic in the immediate vicinity which could obstruct the manoeuvring ship;
- navigation obstacles such as ships at anchor, moored ships, docks, dredgers and hydrographical ships busy at marking navigational;
- operations related to the modernization, reconstruction or construction of new hydro-technical structures and navigation infrastructure, restricting the movement of ships;
- port structures (locks, wharfs, navigational-fixed and floating marks);
- completeness and certainty of navigational information;
- geometrical dimensions of water area (width, depth) and its shape and connections at these occurrences;
- vessel traffic service VTS (international and local regulations);
- hydro meteorological conditions (currents, tides, unprofitable directions of wind, ice);
- competence and experience of the vessel's crew.

To simplify the problem, we assume that for every vessel, the position, velocity and course are known. Additionally, the distance, for $t > 0$, between two ships are given by the formula (Guze, 2011):

$$D_{S_iS_j}(t) = \\ = \sqrt{D_{S_i}^2(t) + D_{S_j}^2(t) - 2D_{S_i}(t)D_{S_j}(t)\cos\left(\varphi_{S_iS_j}(t)\right)} \tag{1}$$

where:

$D_{Si}(t)$ – the distance of ship S_i to point of potential threat of collision at the time t;

$D_{Sj}(t)$ – the distance of ship S_j, point of potential threat of collision at the time t;

$\varphi_{Si\,Sj}(t)$ – the angle of intersection of S_i and S_j ships courses, at the time t.

Every navigational obstacle on the water area generates the potential risk of collision, which can be described by the index $r_g(t)$. For a ship during the passage, this potential risk is changing in time according to a motion vector. The formula to describe this index is given by a two dimensional probability distribution function, which is a combination of a convex distribution on the plain as follows:

$$r_g(x, y, t) = f_k(x, y) \tag{2}$$

where: k – type of vessel.

Taking into account the different types of vessel, the following cases are considered.

Case 1. For the ship at anchor or other navigational objects not moving the function is given by:

$$f_1(x,y) = \begin{cases} 0 & (x,y) \notin K\left((\varphi,\lambda),r\right) \\ \dfrac{1}{\pi r^2} & (x,y) \in K\left((\varphi,\lambda),r\right) \end{cases} \tag{3}$$

where $K((\varphi, \lambda), r)$ is the circle with radius $r > 0$ and with the centre designated by geographical coordinates (Guze, 2011).

Case 2. For the moving ship with fixed course (Guze, 2011):
- for movements on the X axis the one modal probability distributions are correct (Weibull, gamma);
- for movements on the Y axis the Laplace and Normal distribution.

Exemplary, it can be given by the following formula:

$$f_2(x,y) = \\ = \alpha_3 \beta_3^{-\alpha_3} x^{\alpha_3 - 1} \exp\left\{-\left(\frac{x}{\beta_3}\right)^{\alpha_3}\right\} \frac{\lambda_3}{2} \exp\left\{-\lambda_3 \left|y - m_3\right|\right\} \tag{4}$$

where:

(x, y) – a ships position coordinates;

$\alpha_3,\ \beta_3,\ \lambda_3 > 0$ – the parameters are dependent on the type of vessel and its manoeuvring characteristics, additionally;

α_3 – is dependent on the technical-exploitation parameters and hydro-metrological conditions;
β_3 – the scale parameter;
λ_3 – is dependent on the possibility of keeping the course;
$m_3 = D_{S_1S_3}\sin\left(\varphi_{S_1S_3}\right)$.

The estimation of all these parameters and its characteristics is possible by the graphical method or the maximum likelihood method ((α_3 and the method of moments (β_3)).

Case 3. There is no actual information about the ships course changes or there is under consideration the incomplete/uncertain navigational information (Guze, 2011):

$$f_3(x,y) = \frac{f_{N(m_x m_y,\sigma_x\sigma_y)}(x,y)\,\chi_{E(R_x,R_y)}(x,y)}{\iint_{E(R_x,R_y)} f(x,y)\,\mathrm{d}x\mathrm{d}y} \quad (5)$$

where:
$E(R_x, R_y)$ – an ellipse with radii R_x, R_y;
$f_{N(mx\ my,\sigma x\ \sigma y)}(x, y)$ – a density function of the two-dimensional Normal distribution with parameters $m_x m_y$, $\sigma_x\sigma_y$;
$\chi_{E(Rx,Ry)}(x, y)$ – an indicator of the set.

In every moment of time t, their own ship is exposed to the risk of collision generated by units on the water area. Thus the index $r_e(t)$ is given by:

$$r_e(t) = \sum_k a_k r_{g,k}(t) \quad (6)$$

where:
k – number of ships on the water area;
$r_{g,k}(t)$ – the index of risk generated by k-th ship on the water area;
a_k – rank coefficient for k-th ship, where $a_k \geq 0$, $\Sigma a_k = 1$.

Dimensioning of Maritime Traffic Safety by the Smoothness Parameter

Assessment of the safety level for the restricted area of a sea is a complex task in which outside weather conditions and the human factor plays a major role. The navigator's behaviour, their attitude toward risk and psychophysical state are factors which traffic control must evaluate on the basis of incomplete and uncertain data.

The information may only be obtained by analysing the trajectories of vessels and ships manoeuvres in connection with the reaction of navigators on the rapidly changing navigation conditions.

The smoothness of traffic as an indicator was the basis for assessing the quality of traffic (Węgierski, 1971) as well as for the risk assessment used in rail transport (Woch, 1983), and also in air transport (Skorupski, 2010).

Each mode of transport has its own specifics so different characteristics are used to evaluate the smoothness of traffic due to the safety assessment. In this paper we propose the use of a two-dimensional risk index which is determined individually for each vessel on the waters. For each of the components of the index we must define the acceptable range of variation, i.e. does not require the intervention of the navigator (change motion parameters of the ship-course or speed) or traffic surveillance (traffic control).

The safety analysis will use both indexes from Section 2 (($r_g(t)$, $r_e(t)$)) by creating:

- a vessel threat level indicator (SHL) until time T;
- a dynamic indicator significance of the threat posed by a ship (SHI) at time t.

We use the following notations:
n – the number of ships at the restricted area;
$r_{gi}(t)$ – the scale of the risk generated by i-th ship;
$r_{g\mathrm{DOP}}$ – the acceptable level of threat generated by a ship;
$\#A$ – the number of element of the set A;
$r_{e\mathrm{DOP}}$ – the acceptable level of the exposure risk of a ship.

The indicators are given by formulas:

a) SHL – a vessel threat level indicator until time T:

$$\mathrm{SHL} = \frac{\#\left(\left\{t_k : r_g(t_k) > r_{g\mathrm{DOP}}; k = 1,\ldots,m;\ t_k < T\right\}\right)}{n} \quad (7)$$

b) SHI – dynamic indicator significance of the threat posed by a ship at time t:

$$\mathrm{SHI} = \frac{r_g(t)}{\sum_i \frac{r_{gi}(t)}{n}} \quad (8)$$

It is also important for what category of risks we are looking at; people, property or the environment. Every disturbance generated by external factors (vessels, weather) is dangerous to the maritime traffic. It is indispensable for traffic controllers to know when and where they should take actions to resolve a potentially dangerous situation.

Therefore, area A should be divided on a coherent set of separate pieces $A = \bigcup_m A_m$ and for each of those, determine the hazard index.

We use the following notations:
n_m – number of ships at the restricted subarea A_m;

$r_{gi}(t)$ – the scale of the risk generated by i-th ship;
$r_{e\mathrm{DOP}}$ – acceptable level of threat generated by a ship;
M – number of subareas A_m.

The indicators are given by formulas:

a) disturbance traffic index for the sub area $A_m(\mathrm{TSI}_m)$:

$$\mathrm{TSI}_m = \frac{\#\left(\left\{i: r_{gi}(t) > r_{e\mathrm{DOP}}; i = 1,\ldots,n_m\right\}\right)}{n_m} \quad (9)$$

b) disturbance traffic index for the area $A(\mathrm{TSI})$:

$$\mathrm{TSI} = \#\left(\left\{m : \mathrm{TSI}_m > 0\right\}\right) \quad (10)$$

Quantitative assessment of the maritime transport safety should be used obligatory as the key tool for safety management at controlled areas. A very important issue is to provide dynamic information about the risks in graphical form on the needs of the navigator and traffic surveillance (SHL, SHI, TSI_m).

Possibility to define a domain based on the safety parameters in the ECDIS

Safety parameters available in the ECDIS (Weintrit, 2009) do not define directly a ships domain. These authors analysed the possibility of identifying the two-dimensional and in the future three-dimensional domain using the parameters analysed in the article. These problems were condensed down to the determination of the length, width and shape for the two-dimensional domain and in the case of the three-dimensional domain the addition of the depth and shape of the geometric solid. It can be done, according to the results from Sections 2–3.

Furthermore, the analysis of alarms and basic safety parameters, their location in the ECDIS system and the consequent difficulty of access to them would make it advisable to introduce the function “Basic Safety Parameters Settings”. This function would allow the operator, in one tab or window, to define and monitor the basic safety parameters, and activate alarms necessary to ensure safe voyage realization by the ship equipped with ECDIS. It should include viewing and editing, and the activation state of alarm associated with them.

These are (Pietrzykowski & Wielgosz, 2011):

- safety contour;
- safety depth;
- safety scale;
- chart display category;
- “chart priority”;
- CPA/TCPA;
- cross track error – XTE;
- course difference;
- WP approach;
- safety vector (advance in the intersection safety contour);
- area vector (advance in the intersection of area objects);
- Navigational Danger Ring, its radius;
- chart display and ship’s motion (North Up, Head Up, Course Up, Relative Motion, True Motion);
- difference in the position of the vessel from primary and secondary positioning system (Primary / Secondary diverged);
- presentation of AIS targets (on/off);
- presentation of ARPA objects (on/off);
- special areas detecting defined (yes/no);
- presentation of the COG (course over ground) and COW (course over water) vectors (on/off);
- off chart (on/off).

Before the start of a voyage or when the system is restarted, ECDIS should automatically require the operator to define or confirm the values of these safety parameters with the possibility of an automatic switch to the window where the operator activates and edits that alarm. If we use the CPA parameter value to determine the length of the domain DL then the length of the domain takes the value:

$$\mathrm{DL} = 2\ \mathrm{CPA} \quad (11)$$

This results from the fact that this parameter defines a safe distance at which other vessels pass, is widely used, and its interpretation is unambiguous.

Due to the difficulty in determining the safety parameter indicating the width of the domain the designation was proposed based on the analytical relationship between the length and width of the domain. This relationship can be derived on the basis of the ship domain analytical descriptions proposed, *inter alia*, in (Coldwell, 1983; Zhao, Wu & Wang, 1993; Śmierzchalski & Weintrit, 1999; Pietrzykowski, 2008; Pietrzykowski & Uriasz, 2009; Wang et al., 2009):

$$\mathrm{DW} = f(\mathrm{DL}) \quad (12)$$

The simplest figure describing the domain of the ship on the basis of the parameters (DL, DW) is a rectangle. Taking into account the results of statistical research on the shape of the domain, the domain was proposed in the shape of an ellipse inscribed in a rectangle with sides (DL, DW).

When the domain function is implemented in the ECDIS, the domain parameters (DL, DW, in third dimension additionally depths DD, DR) will be generated automatically as a default with the possibility of correction by the navigator (like other safety parameters).

The domain parameters DL and DW can be described taking into account the results from the model proposed in Sections 2 and 3.

Conclusions

The conception of the ship domain model is introduced, and the collision probability model is constructed making use of the ship domain model and ship motion characteristics. The collision probability calculation method based on ship domain is put forward by using the geometric probability model, combining overlapping areas of two ship domains. In addition, collision probability is analyzed from a ship point of view and also other traffic participants. The applied models of risk measures can be used by both navigators and supervisors of traffic. Developing risk measures allows management of security and construction of computers to support the needs of navigators and traffic surveillance. When the solutions herein proposed are implemented by manufacturers and positively verified by navigators in practice, it will be recommendable to consider options for revising the performance standards for ECDIS systems.

Based on the analysis of alarms and indications of the ECDIS system and safety parameters defined by the navigator, the group of parameters and measures necessary for the safe sea passage were proposed particularly for use in restricted areas.

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