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An analysis of domain-based ship collision risk parameters

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ABSTRACT

According to a lot of contemporary research on ship collision avoidance the classic approach parameters – distance at closest point of approach (DCPA) and time to the closest point of approach (TCPA) – are not sufficient for estimating ship collision risk and for planning evasive manoeuvres. Consequently new measures are introduced, often utilizing the concept of a ship domain. Their drawback, up to this point, was the lack of analytic solutions that would make it possible to efficiently use ship domains in real-time systems where computational time is of essence. The current paper aims to change this, offering analytic formulas for domain-based collision risk parameters: degree of domain violation (DDV) and time to domain violation (TDV). Explicit derivations of formulas for DDV and TDV are presented here for any elliptic domain. For domains of other shapes elliptic approximations are discussed, so that the derived formulas could still be used. A comparison of TCPA/DCPA with domain-based parameters is presented, evidencing the superiority of the latter.

1. Introduction

Despite extensive research that has been done on ship safety domains, the classic approach parameters – distance at closest point of approach (DCPA) and time to the closest point of approach (TCPA) remain an industry standard in on board collision avoidance and decision support systems (Chin and Debnath, 2009), especially in Automatic Radar Plotting Aid (ARPA). There is certainly no lack of evidence that a ship domain is more than a theoretical concept. As of late, in (Hansen et al., 2013, Wang and Chin, 2016) domain models based on real AIS data from southern Danish waters and Singapore Port area respectively have been developed. Those domain models show significant similarities to classic ship domain shapes of the past, both theoretical and empirical (Fuji and Tanaka, 1971; Goodwin, 1975; Davis et al., 1982; Coldwell, 1983). A form of a ship domain has also been suggested by an AIS data-based analysis of distances between ships in convoys in ice conditions (Goerlandt et al., 2016). Despite all the abovementioned research the world of commercial system designers and manufacturers has still not warmed up to the idea of a ship domain. Even brand new systems of state-of-the art functionality choose to rely on combination of TCPA and DCPA (Pietrzykowski et al., 2012).

If ship domains are used in practice, it is mostly in marine traffic engineering, e.g. for determining the capacity of traffic lanes and assessing statistical collision risk (Rawson et al., 2014; Liu et al., 2015). Yet even when this purpose is considered, the domain-oriented researchers are in minority - the synonymous terms of a safe distance or safety radius dominate in this kind of projects (Mou et al., 2010; Wen et al., 2015; Zhang et al., 2015a; Li and Pang, 2013; Sang et al., 2015; Xiao et al., 2015; Goerlandt et al., 2012). The same is true for collision avoidance systems and safe path planning: the majority of researchers use concepts of a safe distance or diameter (Tam et al., 2009; Tam and Bucknall, 2013; Zhang et al., 2015b; Perera and Guedes Soares, 2015; Lee et al., 2015) and compare those values to DCPA when assessing collision risk. However, it must be noted that ship domains – and context-specific approach in general – are utilized in alerts-oriented collision risk decision support systems, whose authors (Baldauf et al., 2011; Bukhari et al., 2013; Simsir et al., 2014 and Goerlandt et al., 2015) realize the limitations of DPCA-TCPA based solutions and opt for more advanced alternatives.

When compared to ship domains, TCPA/DCPA major flaw is their ignorance of the target's bearing and aspect. But it is not its only limitation. Another related problem is that if we assume a large safe distance (which may be reasonable in some cases, e.g. in restricted visibility) then TCPA may be a long time value, even if the safe distance is soon to be violated. In the worst case scenario TCPA may be practically irrelevant – the close quarters situation may happen long before the closest point of approach is actually reached. Therefore in (Lenart, 2015) a new collision threat parameter – time to safe distance (meaning: time to violating the safe distance) was introduced. Lenart presented an extensive analysis of DCPA and TCPA and based on that – argued and evidenced the superiority of newly defined time to safe distance over TCPA.

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The current paper addresses the abovementioned limitations of TCPA/DCPA by offering their domain-based equivalents. At the same time, the authors are aware of the fact that complexity of ship domains and related computations is a serious discouraging factor when their practical applications in commercial systems are considered. After all, the computational time is of essence in on-board decision support systems and in that matter it is hard to compete with simple analytical formulas for TCPA and DCPA. This problem however can be overcome if elliptic domains or elliptic approximations of other-shaped domains are used. As the paper shows, practically any domain can be approximated with reasonable accuracy by a decentralised ellipse and once this is done, all necessary formulas can be derived analytically. The rest of the paper is organized as follows. In Section 2 the issue of elliptic approximation of ship domain is discussed. An analysis of general domain-based parameters is provided in Section 3, where a degree of domain violation (DDV) is defined. In Section 4 a new parameter – time to domain violation (TDV) is introduced, which is a domain-based generalization of time to safe distance by (Lenart, 2015). Examples of applying the proposed parameters are given in Section 5, followed by paper's conclusions in Section 6.

2. Elliptic approximation of a ship domain

The major advantages of an ellipse as an approximating figure are its flexibility and computational simplicity. As for the former, a decentralised elliptic domain used here (Fig. 1) is described by four length-dependent parameters:

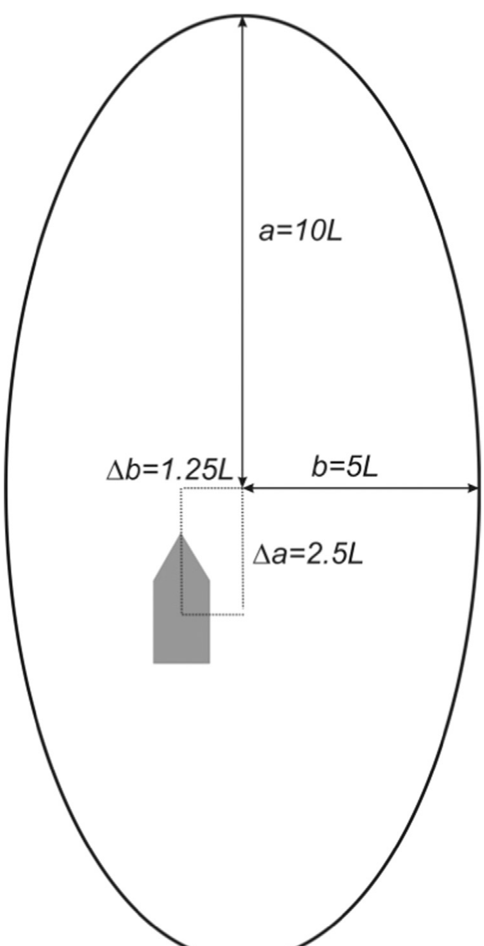

Fig. 1. A decentralised elliptic ship domain (L – ship's length).

a – semi-major axis,
b – semi-minor axis,
Δa – a ship's displacement from the ellipse's centre towards aft along the semi-major axis,
Δb – a ship's displacement from the ellipse's centre towards port along the semi-minor axis.

The first two variables make it possible to specify the domain's length and width, the other two – to vary the sizes of the fore, aft, starboard and port sectors. In practice this is enough to make a domain compliant with COLREGS (IMO, 1972, Cockcroft and Lameijer, 2011) by favouring passing astern and manoeuvres to starboard, while reflecting navigator's perception of collision risk. At the same time, an ellipse is the most complex geometric figure which still makes it possible to formulate all necessary equations as quadratic polynomials, which can be solved analytically. Finally, it is also worth noting that according to many researchers ship domains actually are ellipses (Fuji and Tanaka, 1971; Davis et al., 1982; Coldwell, 1983; Hansen et al., 2013; Liu et al., 2015).

In (Szlapczynski and Szlapczynska, 2015) the authors have shown how a ship domain can be approximated by a polygon and that 16 nodes is sufficient for a quality approximation with additional nodes carrying little to no significant information. Below the reverse process will be shown. Contemporary ship domain models are often based on empirical data, which means that the researchers either use polygonal shapes (Wang and Chin, 2016; Rawson *et al.*, 2014, Pietrzykowski et al. 2009) or at least these shapes come from a set of points around a central ship that initially form a polygon (Hansen et al., 2013).

The literature is rich in algorithms approximating given shapes (including polygons) with regular figures. In particular, various methods of bounding a set of points with an ellipse are discussed in detail in (van Loan, 2008; Gander *et al.*, 1994; Rosin, 1993). In (van Loan, 2008) it has been shown there that using a conic representation of an ellipse (pages 8–9) allows to reduce the approximation to a linear least squares problem with five unknowns (page 47). In conic representation a set of points (x,y) defines an ellipse if:

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F=0 \tag{1}$$

where

$$B^2 - 4AC<0 \tag{2}$$

and (to avoid degenerate matrix):

$$\frac{D^2}{4A} + \frac{E^2}{4C} - F>0 \tag{3}$$

Without loss of generality it may be assumed that A = 1, which gives:

$$x^2 + Bxy + Cy^2 + Dx + Ey + F=0 \tag{4}$$

$$B^2 - 4C<0 \tag{5}$$

$$\frac{D^2}{4} + \frac{E^2}{4C} - F>0 \tag{6}$$

For such a defined ellipse and a given set of points $\{(x_1,y_1),\ldots(x_n,y_n)\}$, the distance (in the least squares sense) from the ellipse to the set of points is:

$$dist = \sum_{i=0}^{n} (x_i^2 + x_i y_i B + y_i^2 C + x_i D + y_i E + F)^2 \tag{7}$$

The values of parameters B, C, D, E, F minimizing (7) can be found by various deterministic iterative algorithms (van Loan, 2008; Gander et al., 1994; Rosin, 1993). In (Szlapczynski and