TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 9
Number 1
March 2015

DOI: 10.12716/1001.09.01.17

A Simulative Comparison of Ship Domains and Their Polygonal Approximations

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ABSTRACT: The paper investigates the impact of a precise ship domain shape on the size of collision avoidance manoeuvres. The considered collision avoidance manoeuvres include both course and speed alterations. Various ship domains are compared with their polygonal approximations, which vary in the number of points of a domain contour and placement of these points. The best of all considered approximations is determined in the course of simulation experiments performed for head-on, crossing and overtaking situations. The chosen number and placement of contour points combine precision of domain approximation with reasonable computational time.

1 INTRODUCTION

A ship domain (Coldwell, 1983; Davis 1982) is generally thought as the space around the ship, which the navigator wants to keep clear of other objects (including ships). Ship domain models are in abundance and the new ones are being continuously proposed, either based on theoretical analyses or real data (Hansen et al., 2013). They are used in marine traffic engineering, e.g. for determining the capacity of traffic lanes and assessing collision risk (Pietrzykowski, 2008; Montewka et al., 2011; Xiang et al., 2013), as well as in collision avoidance for determining safe manoeuvres (Śmierzchalski, 2000). The shape and size of a ship domain is usually dependent on ship's length and speed (Fuji and Tanaka, 1971), though parameters of other ships may also be taken into account (Pietrzykowski and Uriasz, 2009). Ship domains are often given explicitly as geometrical figures but (especially in case of restricted waters) they may also be given as functions proposed on the basis of safety parameters defined in the ECDIS (Pietrzykowski and Wielgosz, 2011; Weintrit, 2006; Weintrit, 2009). This paper abstracts from the more general traffic engineering issues and focuses on the practical impact of a domain's shape on determining course and speed alteration manoeuvres in encounter situations (Szłapczyński, 2007). While the collision avoidance manoeuvres are often strongly dependent on the domain's size (the larger the domain, the larger the manoeuvres), the precise impact of its shape has not been researched before. Various researchers develop their domain models based on empirical data (distances between ships for different relative courses and bearings), collision risk assessments, COLREGS and good marine practice. The differences between the proposed shapes are sometimes very subtle, hence the present authors' idea to check, whether those small differences actually translate to different navigational decisions (collision avoidance manoeuvres) and to what extent. Obviously, in many real situations navigational decisions depend on reasons other than assumed domain shapes and sizes. Actual course alterations may be much larger than those determined to avoid a ship domain violation. In such cases ship domains are practically irrelevant and therefore these situations are of no use for this research and are not taken into account in the simulation experiments. For the purpose of this research it is assumed that we are dealing with isolated cases when course alteration manoeuvres are based solely on ship domains and that avoiding domain violations is both necessary and sufficient condition for the alteration to be safe.

Because of their various sizes, the ship domains cannot be compared directly with each other. Therefore in the experiments presented in the paper each of the considered domains is compared with a series of its polygonal approximations containing 8, 16 or 32 points placed uniformly or non-uniformly (constant or varying angular distances between points lying on the domain's boundary). The number of points is of key importance because it affects both the precision of results and the computational time. In a decision support system potential domain violations are usually checked within multiple loops, thus being the most frequent operations and largely contributing to the overall computational time. Doubling the number of points in a ship domain model practically doubles the computational time of determining a safe trajectory or a collision avoidance manoeuvre. Therefore, the paper aims to investigate the impact of approximation points and their placement on the size of course and speed alterations performed to avoid collisions.

The remaining part of the paper is organized as follows. In Section 2 all considered domains are briefly described. The prepared encounter scenarios and polygonal approximations of domains are presented in Section 3 and the results of the simulation experiments are shown and discussed in Section 4. Based on these results, a summary and conclusions are given in Section 5.

2 SHIP DOMAINS TAKEN INTO ACCOUNT IN THE COMPUTER SIMULATION EXPERIMENTS

The shapes used in the experiments are those of ship domains according to Fuji (1971), Davis (1982), Coldwell (1983) and Pietrzykowski (2009). Two slightly differing shapes have been applied in case of Coldwell's domain (one for head-on and crossing encounters and another one for overtaking) and six shapes in case of Pietrzykowski (three dedicated for fuzzy domains and three for the crisp ones). The shapes of ship domains according to Fuji, Coldwell and Davis are commonly known and therefore are not reproduced here. Examples of more interesting, irregular ship domain shapes according to Pietrzykowski (2009) are shown in Figures 1 and 2. The fuzzy domain utilizes a navigational safety level γ. The bipolar grid in all figures features circles, whose radiuses are 0.5, 1, 1.5 and 2 nautical miles.

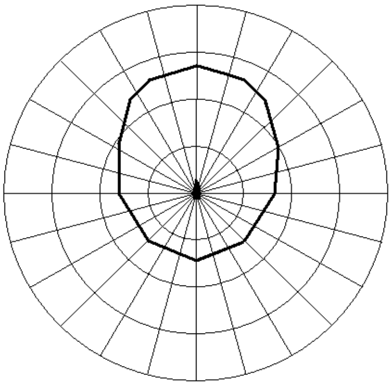

Figure 1. Fuzzy domain according to Pietrzykowski and Uriasz with γ parameter (navigational safety level) set to 0.5.

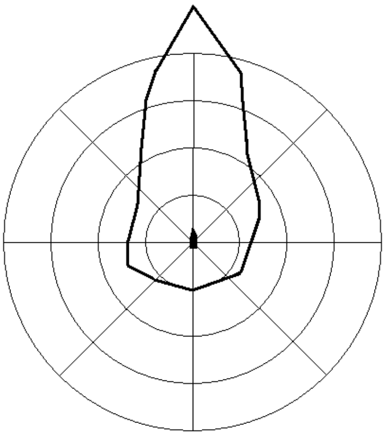

Figure 2. Fuzzy domain according to Pietrzykowski and Uriasz dedicated to head-on encounters.

3 SIMULATION EXPERIMENTS (ENCOUNTER SCENARIOS AND POLYGONAL APPROXIMATIONS OF DOMAINS)

Three types of one-on-one encounter scenarios are used throughout the simulation experiments: head-on, crossing and overtaking. The differences between ship courses are 180, 90 and 0 degrees respectively, and the speeds and initial positions are such that ships would collide if neither of them manoeuvred. The distances between ships vary in the scenarios, depending on a particular domain, which is used. The distances are deliberately set in such a way, that the necessary safe course alteration manoeuvre would be between 15 and 20 degrees and (in case of crossing encounters) speed reduction manoeuvres would be in the same range (speed reduced by 4 to 6 knots) for all ship domains.

If we assume that a course alteration is made so as to avoid violating a target's domain, than clearly both shape and size of domain is of importance. It is illustrated in Figures 3 and 4, where courses which lead to violating ship domains are shown for a circular domain (safe distance often used in collision avoidance systems) and elliptical domain respectively. Forbidden (collision) course sectors vary in both cases due to using different domains.

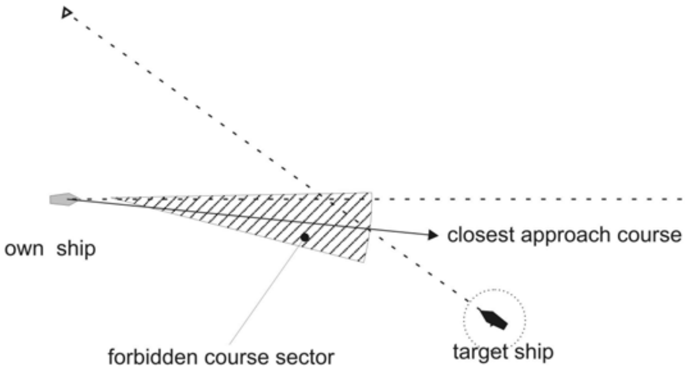

Figure 3. Collision course sector for a given safe distance.

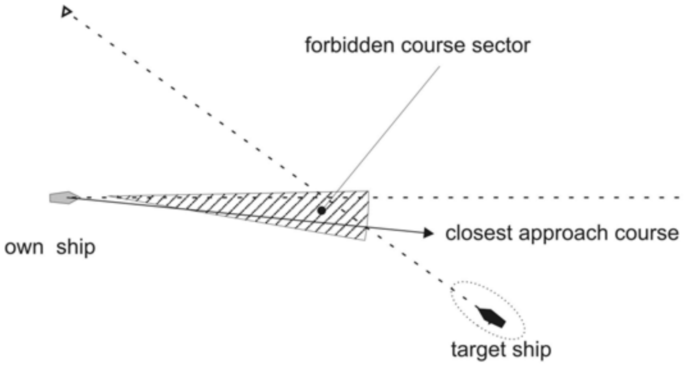

Figure 4. Collision course sector for a given target's domain.

The algorithm for determining the minimal acceptable course alterations (and consequently - collision course sectors) has been described in detail in (Szłapczyński, 2007). It is briefly recalled here for the readers convenience. In the algorithm (Figure 5), the course alteration is modified iteratively until target's domain is not violated (the approach factor f_{min} is larger than 1) and the accuracy is sufficient (the error is smaller than given value of the parameter δψ).

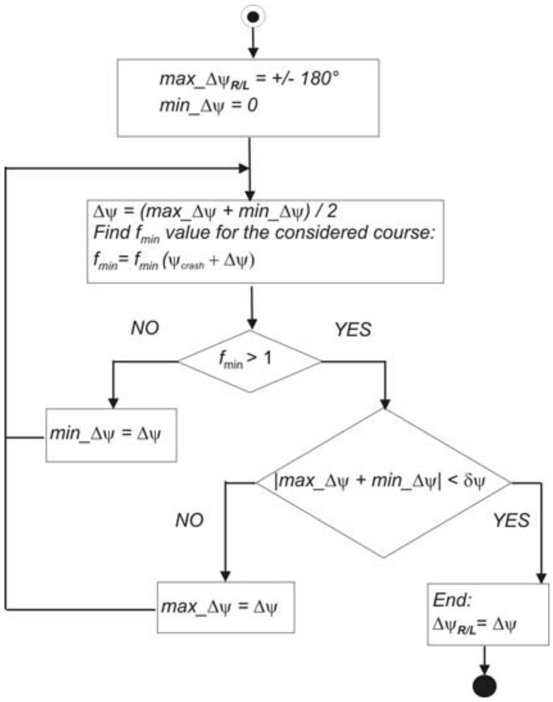

Figure 5. Algorithm determining minimal course alteration for a give ship domain based on approach factor f_{min}.

For each domain five polygonal approximations are compared. In each case the approximation is done automatically: the coordinates of points on the original domain boundaries are determined first and then are joined by straight segments so as to form polygons. The approximations vary in the number points and their placement: 8-point, 16-point and 32-point approximations are used. The 8-point and 16-point approximations appear in two variants each: either uniform angular distances or non-uniform ones are used. For the uniform angular distances the points on the approximated domain boundary are placed in either 45 degree intervals (8-point approximation) or 22.5 degree intervals (16 degree intervals). For the non-uniform angular distances, the points on the approximated domain boundary are placed as follows. For 8 points: 0, 30, 90, 150, 180, 210, 270 and 330 degrees. For 16 points: 0, 15, 30, 60, 90, 120, 150, 165, 180, 195, 210, 240, 270, 300, 330 and 345 degrees. The reason for testing non-uniform angular distances as well as uniform ones is that the left and right sides of a ship domain are often easier to approximate than their fore and aft and therefore it makes sense to save on points at the sides and use the extra points in the front and back. Examples of uniform and non-uniform placement of points in 8-point polygonal approximations of ship domains are given in Figures 6 to 9.

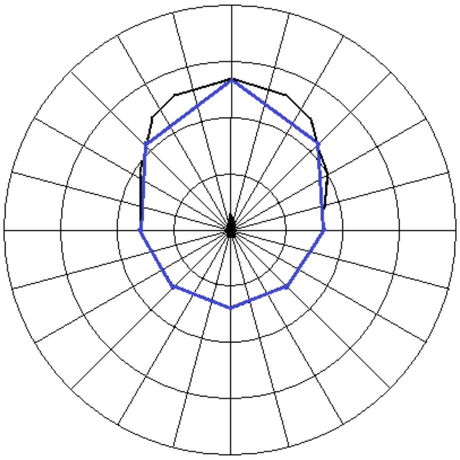

Figure 6. An 8-point approximation of a ship domain from Fig. 1. (uniform placement of points)

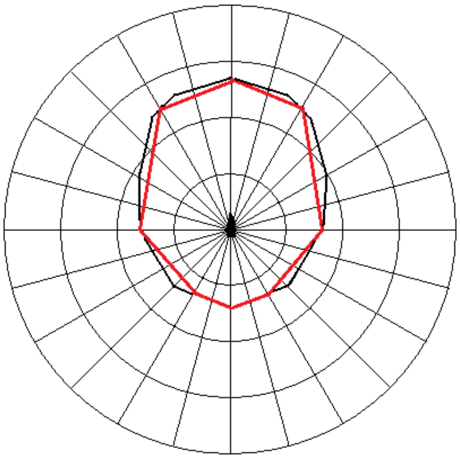

Figure 7. An 8-point approximation of a ship domain from Fig. 1. (non-uniform placement of points)

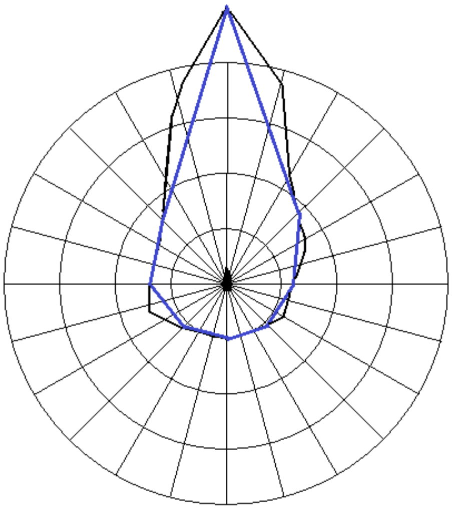

Figure 8. An 8-point approximation of a ship domain from Fig. 2. (uniform placement of points)

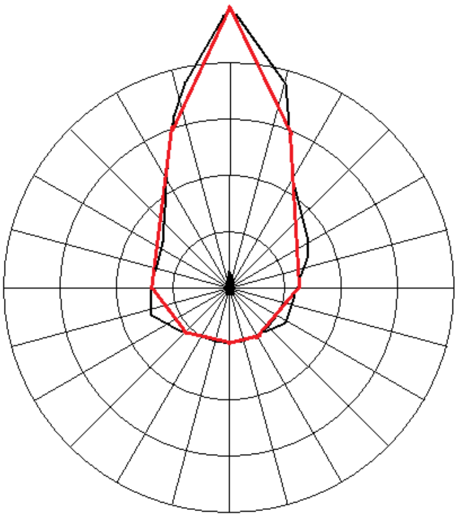

Figure 9. An 8-point approximation of a ship domain from Fig. 2. (non-uniform placement of points)

4 RESULTS OF THE EXPERIMENTS

In Tables 1 to 3 the resulting course alteration manoeuvres are shown for each scenario and each approximation of a given ship domain. Collision course sectors are given in Table 1 and the errors of approximation (the differences between values obtained for original domains and the polygonal approximations) are given in Tables 2 (manoeuvres to starboard) and 3 (manoeuvres to port). In Tables 4 and 5 the values of speed reduction and the errors of approximation (the differences between values obtained for original domains and the polygonal approximations) are shown respectively. Some of the original domains are also polygons with vertices placed uniformly and as a result polygonal approximations will return no errors. Therefore two separate averages are computed, with one of them ignoring those polygonal domains (last rows of Tables 2 to 5).

As can be seen in the Tables 2 to 5, the 8-point approximations give imprecise results. For course alteration manoeuvres sometimes the error is nearly 4 degrees (over 24%), which is unacceptable. The volume of errors varies between scenarios, with the average course alteration errors being about 10% for manoeuvres to port (Table 2) and 7% for manoeuvres to starboard (Table 3). The values of course alteration errors are similar for uniform and non-uniform placement of approximation points. In case of speed reduction manoeuvres the uniform placement of points again returns significant errors, the average error being about 7% (Table 5). However the results for non-uniform approximation are much better: the average error is under 4% even when the relatively easy cases (polygonal domains) are excluded.

Table 1. Collision course sectors for original domains and their automatic polygonal approximations

Domain	Encounter type	Original domain	8 points (uniform)	8 points (non-uniform)	16 points (uniform)	16 points (non-uniform)	32 points (non-uniform)
Fuji	head-on	(-20.05; 20.05)	(-19.52; 19.52)	(-19.20; 19.20)	(-19.82; 19.82)	(-19.78; 19.78)	(-19.97; 19.97)
	crossing	(-20.18; 16,17)	(-18.17; 14.29)	(-18.67; 14.81)	(-18.84; 15.69)	(-19.39; 16.09)	(-19.90; 16.02)
	overtaking	(-20.49; 20.49)	(-17.34; 17.34)	(-19.42; 19.42)	(-19.82; 19.82)	(-19.76; 19.76)	(-20.24; 20.24)
Davis	head-on	(-23.90; 19.30)	(-20.91; 17.66)	(-20.81; 16.61)	(-23.85; 19.17)	(-23.70; 18.96)	(-23.74; 19.17)
	crossing	(-22.09; 18.37)	(-20.30; 18.16)	(-21.84; 17.87)	(-21.61; 18.19)	(-21.96; 17.96)	(-22.04; 18.30)
	overtaking	(-20,53, 16,31)	(-18,75, 15,15)	(-18,39, 14,69)	(-20,47, 16,20)	(-19,94, 16,11)	(-20,48, 16,26)
Coldwell	head-on	(-21.90; 10.85)	(-20.85; 10.83)	(-20.34; 10.47)	(-21.57; 10.83)	(-21.58; 10.83)	(-21.71; 10.83)
	crossing	(-24.55; 15.15)	(-20.21; 14.72)	(-21.27; 14.75)	(-23.15; 14.79)	(-24.20; 14.83)	(-24.07; 14.85)
	overtaking	(-16.24; 16.24)	(-12.33; 12.33)	(-13.77; 13.77)	(-14.93; 14.93)	(-16.12; 16.12)	(-15.72; 15.72)
Pietrzykowski fuzzy, γ=0.5	head-on	(-18.00; 16.97)	(-17.01; 16.60)	(-15.46; 15.46)	(-17.24; 16.66)	(-17.87; 16.86)	(-17.86; 16.94)
	crossing	(-21.04; 19.02)	(-18.05; 17.24)	(-20.51; 18.65)	(-21.04; 18.25)	(-20.54; 18.68)	(-21.04; 18.95)
	overtaking	(-19.06; 17.82)	(-18.07; 17.39)	(-16.08; 16.08)	(-18.13; 17.44)	(-19.02; 17.66)	(-18.87; 17.79)
Pietrzykowski fuzzy, γ=0.1	head-on	(-21.92; 20.93)	(-19.91; 18.25)	(-17.49; 17.39)	(-21.70; 20.57)	(-21.51; 20.63)	(-21.71; 20.60)
	crossing	(-25.37; 22.07)	(-23.15; 22.03)	(-25.22; 21.68)	(-24.88; 22.06)	(-25.25; 21.76)	(-25.37; 22.07)
	overtaking	(-18.09; 17.16)	(-15.93; 14.63)	(-14.40; 14.34)	(-17.91; 16.92)	(-17.70; 16.82)	(-17.92; 16.93)
Pietrzykowski crisp, Dmin	head-on	(-19.11; 19.11)	(-19.08; 19.08)	(-17.24; 17.24)	(-19.11; 19.11)	(-18.30; 18.30)	(-19.08; 19.08)
	crossing	(-19.36; 17.92)	(-19.36; 17.91)	(-19.36; 16.82)	(-19.36; 17.92)	(-19.36; 16.91)	(-19.37; 17.91)
	overtaking	(-19.87; 19.87)	(-19.86; 19.86)	(-19.19; 19.19)	(-19.87; 19.87)	(-19.78; 19.78)	(-19.83; 19.83)
Pietrzykowski crisp, Dmean	head-on	(-16.00; 16.00)	(-16.00; 16.00)	(-15.22; 15.22)	(-16.00; 16.00)	(-15.81; 15.81)	(-15.96; 15.96)
	crossing	(-19.05; 19.45)	(-19.05; 19.45)	(-18.80; 17.20)	(-19.05; 19.45)	(-18.80; 17.20)	(-19.04; 19.42)
	overtaking	(-16.80; 16.80)	(-16.80; 16.80)	(-15.53; 15.53)	(-16.80; 16.80)	(-16.46; 16.46)	(-16.75; 16.75)

Pietrzykowski crisp, Dmax	head-on	(-20.05; 20.05)	(-20.05; 20.05)	(-20.00; 20.00)	(-20.05; 20.05)	(-20.05; 20.05)	(-20.04; 20.04)
	crossing	(-23.57; 23.44)	(-23.33; 23.44)	(-23.53; 20.99)	(-23.54; 23.44)	(-23.54; 20.99)	(-23.55; 23.43)
	overtaking	(-16.63; 16.63)	(-16.63; 16.63)	(-16.09; 16.07)	(-16.62; 16.62)	(-16.63; 16.63)	(-16.62; 16.62)
Pietrzykowski (head-on dedicated domain)	head-on	(-16.17; 15.27)	(-15.22; 14.79)	(-16.02; 14.70)	(-15.49; 15.05)	(-16.06; 15.17)	(-15.81; 15.25)

Table 2. Differences between manoeuvres to port for original domains and their automatic polygonal approximations (absolute and relative values)

Domain	**Encounter type**	**8 points (uniform)**	**8 points (non-uniform)**	**16 points (uniform)**	**16 points (non-uniform)**	**32 points (non-uniform)**
Fuji	head-on	0.53 / 2.63%	0.85 / 4.22%	0.23 / 1.15%	0.27 / 1.37%	0.08 / 0.38%
	crossing	2.01 / 9.96%	1.52 / 7.51%	1.34 / 6.64%	0.79 / 3.92%	0.29 / 1.42%
	overtaking	3.15 / 15.39%	1.07 / 5.20%	0.67 / 3.27%	0.73 / 3.54%	0.25 / 1.23%
Davis	head-on	2.99 / 12.51%	3.09 / 12.92%	0.04 / 0.18%	0.20 / 0.83%	0.15 / 0.64%
	crossing	1.79 / 8.11%	0.25 / 1.14%	0.48 / 2.19%	0.13 / 0.60%	0.05 / 0.25%
	overtaking	1.78 / 8.67%	2.14 / 10.43%	0.07 / 0.32%	0.59 / 2.89%	0.05 / 0.27%
Coldwell	head-on	1.04 / 4.77%	1.56 / 7.12%	0.33 / 1.51%	0.32 / 1.46%	0.19 / 0.85%
	crossing	4.34 / 17.67%	3.28 / 13.38%	1.41 / 5.73%	0.35 / 1.43%	0.48 / 1.97%
	overtaking	3.91 / 24.09%	2.47 / 15.22%	1.31 / 8.05%	0.12 / 0.74%	0.52 / 3.18%
Pietrzykowski fuzzy, γ=0.5	head-on	0.99 / 5.49%	2.54 / 14.10%	0.76 / 4.21%	0.12 / 0.67%	0.13 / 0.73%
	crossing	2.99 / 14.20%	0.53 / 2.51%	0.00 / 0.00%	0.49 / 2.35%	0.00 / 0.00%
	overtaking	0.99 / 5.19%	2.98 / 15.62%	0.93 / 4.90%	0.04 / 0.23%	0.19 / 0.98%
Pietrzykowski fuzzy, γ=0.1	head-on	2.01 / 9.17%	4.43 / 20.20%	0.22 / 1.00%	0.41 / 1.85%	0.21 / 0.95%
	crossing	2.22 / 8.75%	0.14 / 0.56%	0.48 / 1.91%	0.12 / 0.48%	0.00 / 0.00%
	overtaking	2.16 / 11.96%	3.69 / 20.40%	0.19 / 1.03%	0.40 / 2.19%	0.18 / 0.97%
Pietrzykowski crisp, Dmin	head-on	0.02 / 0.12%	1.87 / 9.78%	0.00 / 0.00%	0.80 / 4.20%	0.02 / 0.12%
	crossing	0.00 / 0.00%	0.00 / 0.00%	0.00 / 0.00%	0.00 / 0.00%	0.01 / 0.06%
	overtaking	0.01 / 0.06%	0.68 / 3.43%	0.00 / 0.00%	0.10 / 0.50%	0.04 / 0.22%
Pietrzykowski crisp, Dmean	head-on	0.00 / 0.00%	0.78 / 4.88%	0.00 / 0.00%	0.19 / 1.17%	0.03 / 0.21%
	crossing	0.00 / 0.00%	0.25 / 1.33%	0.00 / 0.00%	0.25 / 1.33%	0.01 / 0.06%
	overtaking	0.00 / 0.00%	1.26 / 7.52%	0.00 / 0.00%	0.34 / 2.03%	0.04 / 0.26%
Pietrzykowski crisp, Dmax	head-on	0.00 / 0.00%	0.05 / 0.27%	0.00 / 0.00%	0.00 / 0.00%	0.01 / 0.05%
	crossing	0.23 / 0.98%	0.03 / 0.14%	0.02 / 0.09%	0.02 / 0.09%	0.01 / 0.05%
	overtaking	0.00 / 0.00%	0.54 / 3.24%	0.01 / 0.07%	0.00 / 0.00%	0.01 / 0.07%
Pietrzykowski (head-on dedicated domain)	head-on	0.96 / 5.91%	0.15 / 0.95%	0.68 / 4.21%	0.11 / 0.68%	0.36 / 2.24%
Average difference		*1.3648 / 6.61%*	*1.446 / 7.28%*	*0.3668 / 1.86%*	*0.2756 / 1.33%*	*0.1324 / 0.69%*
Average difference without crisp polygonal domains by Pietrzykowski		*2.12 / 10.26%*	*1.92 / 9.46%*	*0.57 / 2.89%*	*0.32 / 1.58%*	*0.20 / 1.00%*

Table 3. Differences between manoeuvres to starboard for original domains and their automatic polygonal approximations (absolute and relative values)

Domain	**Encounter type**	**8 points (uniform)**	**8 points (non-uniform)**	**16 points (uniform)**	**16 points (non-uniform)**	**32 points (non-uniform)**
Fuji	head-on	0.53 / 2.63%	0.85 / 4.22%	0.23 / 1.15%	0.27 / 1.37%	0.08 / 0.38%
	crossing	1.88 / 11.62%	1.36 / 8.42%	0.48 / 2.99%	0.08 / 0.48%	0.15 / 0.95%
	overtaking	3.15 / 15.39%	1.07 / 5.20%	0.67 / 3.27%	0.73 / 3.54%	0.25 / 1.23%
Davis	head-on	1.65 / 8.54%	2.69 / 13.94%	0.13 / 0.68%	0.34 / 1.76%	0.13 / 0.68%
	crossing	0.21 / 1.14%	0.49 / 2.69%	0.18 / 0.96%	0.41 / 2.21%	0.07 / 0.36%
	overtaking	1.16 / 7.14%	1.63 / 9.97%	0.11 / 0.67%	0.21 / 1.28%	0.05 / 0.34%
Coldwell	head-on	0.02 / 0.20%	0.38 / 3.54%	0.02 / 0.20%	0.02 / 0.20%	0.02 / 0.20%
	crossing	0.43 / 2.83%	0.40 / 2.61%	0.36 / 2.39%	0.32 / 2.10%	0.30 / 1.96%
	overtaking	3.91 / 24.09%	2.47 / 15.22%	1.31 / 8.05%	0.12 / 0.74%	0.52 / 3.18%
Pietrzykowski fuzzy, γ=0.5	head-on	0.37 / 2.20%	1.52 / 8.93%	0.32 / 1.88%	0.11 / 0.65%	0.03 / 0.19%
	crossing	1.78 / 9.36%	0.36 / 1.91%	0.77 / 4.04%	0.34 / 1.79%	0.07 / 0.35%
	overtaking	0.43 / 2.40%	1.74 / 9.74%	0.38 / 2.16%	0.16 / 0.92%	0.03 / 0.18%
Pietrzykowski fuzzy, γ=0.1	head-on	2.68 / 12.81%	3.54 / 16.90%	0.36 / 1.73%	0.30 / 1.42%	0.33 / 1.57%
	crossing	0.04 / 0.20%	0.40 / 1.79%	0.01 / 0.05%	0.31 / 1.39%	0.00 / 0.00%
	overtaking	2.53 / 14.72%	2.82 / 16.45%	0.24 / 1.41%	0.34 / 1.98%	0.23 / 1.34%
Pietrzykowski crisp, Dmin	head-on	0.02 / 0.12%	1.87 / 9.78%	0.00 / 0.00%	0.80 / 4.20%	0.02 / 0.12%
	crossing	0.01 / 0.06%	1.10 / 6.13%	0.00 / 0.00%	1.01 / 5.64%	0.01 / 0.06%
	overtaking	0.01 / 0.06%	0.68 / 3.43%	0.00 / 0.00%	0.10 / 0.50%	0.04 / 0.22%

Pietrzykowski crisp, Dmean	head-on	0.00 / 0.00%	0.78 / 4.88%	0.00 / 0.00%	0.19 / 1.17%	0.03 / 0.21%
	crossing	0.00 / 0.00%	2.24 / 11.53%	0.00 / 0.00%	2.24 / 11.53%	0.02 / 0.11%
	overtaking	0.00 / 0.00%	1.26 / 7.52%	0.00 / 0.00%	0.34 / 2.03%	0.04 / 0.26%
Pietrzykowski crisp, Dmax	head-on	0.00 / 0.00%	0.05 / 0.27%	0.00 / 0.00%	0.00 / 0.00%	0.01 / 0.05%
	crossing	0.00 / 0.00%	2.45 / 10.45%	0.00 / 0.00%	2.45 / 10.45%	0.01 / 0.05%
	overtaking	0.00 / 0.00%	0.56 / 3.37%	0.01 / 0.07%	0.00 / 0.00%	0.01 / 0.07%
Pietrzykowski (head-on dedicated domain)	head-on	0.48 / 3.17%	0.57 / 3.74%	0.22 / 1.44%	0.10 / 0.65%	0.02 / 0.14%
Average difference		*0.8516 / 4.74%*	*1.3312 / 7.30%*	*0.232 / 1.33%*	*0.4516 / 2.32%*	*0.0988 / 0.57%*
Average difference without crisp polygonal domains by Pietrzykowski		*1.3281 / 7.22%*	*1.3931 / 7.56%*	*0.3618 / 2.00%*	*0.26 / 1.32%*	*0.1425 / 0.79%*

Table 4. Speed reduction allowing for safe passage for original domains and their automatic polygonal approximations (crossing encounters only)

Domain	**Encounter type**	**8 points (uniform)**	**8 points (non-uniform)**	**16 points (uniform)**	**16 points (non-uniform)**	**32 points (non-uniform)**
Fuji	4.39	4.14	4.15	4.17	4.24	4.33
Davis	4.36	4.01	4.31	4.34	4.33	4.36
Coldwell	4.36	4.33	4.34	4.34	4.36	4.36
Pietrzykowski, fuzzy, γ=0.5	4.62	4.02	4.52	4.62	4.53	4.62
Pietrzykowski, fuzzy, γ=0.1	5.28	4.81	5.22	5.19	5.22	5.19
Pietrzykowski, crisp, Dmin	4.33	4.33	4.33	4.33	4.33	4.33
Pietrzykowski, crisp, Dmean	4.26	4.26	4.21	4.26	4.21	4.26
Pietrzykowski, crisp, Dmax	5.09	5.09	5.08	5.09	5.08	5.08

Table 5. Difference between safe speed reduction values computed for original domains and their automatic polygonal approximations (absolute and relative values)

Domain	**8 points (uniform)**	**8 points (non-uniform)**	**16 points (uniform)**	**16 points (non-uniform)**	**32 points (non-uniform)**
Fuji	0.25 / 5.68%	0.23 / 5.34%	0.22 / 5.01%	0.15 / 3.34%	0.06 / 1.34%
Davis	0.35 / 8.07%	0.04 / 1.01%	0.01 / 0.34%	0.03 / 0.67%	0.00 / 0.00%
Coldwell	0.03 / 0.67%	0.01 / 0.34%	0.01 / 0.34%	0.00 / 0.00%	0.00 / 0.00%
Pietrzykowski, fuzzy, γ=0.5	0.60 / 13.00%	0.10 / 2.22%	0.00 / 0.00%	0.09 / 1.90%	0.00 / 0.00%
Pietrzykowski, fuzzy, γ=0.1	0.47 / 8.88%	0.06 / 1.11%	0.09 / 1.66%	0.06 / 1.11%	0.09 / 1.66%
Pietrzykowski, crisp, Dmin	0.00 / 0.00%	0.00 / 0.00%	0.00 / 0.00%	0.00 / 0.00%	0.00 / 0.00%
Pietrzykowski, crisp, Dmean	0.00 / 0.00%	0.04 / 1.03%	0.00 / 0.00%	0.04 / 1.03%	0.00 / 0.00%
Pietrzykowski, crisp, Dmax	0.00 / 0.00%	0.01 / 0.29%	0.00 / 0.00%	0.01 / 0.29%	0.01 / 0.29%
Average difference	*0.2125 / 4.54%*	*0.0612 / 2.55%*	*0.0412 / 0.92%*	*0.0475 / 1.04%*	*0.0187 / 0.38%*
Average difference without crisp domains by Pietrzykowski	*0.34 / 7.26%*	*0.088 / 3.82%*	*0.066 / 1.47%*	*0.066 / 1.40%*	*0.03 / 0.6%*

Both 16-point approximations fare much better than their 8-point equivalents: for course alterations the average error is about 3 to 4 times smaller, for speed reduction 2 to 3 times smaller. For both kinds of manoeuvres the 16-point approximation with non-uniform placement of points is considerably better than the one with points placed uniformly (especially, if polygonal domains are excluded). The average errors diminish to about 1.5% - 2% for course alteration manoeuvres (Tables 2 and 3) and to 1.4% - 1.5% for speed reduction manoeuvres (Table 5).

Unsurprisingly, applying 32-point approximation (with uniform placement of points) gives even more precise results: one can observe further diminishments in both course alteration errors and speed reduction errors. However, the benefits of using the extra 16 points are relatively insignificant this time. The average error diminishes from 1.5% - 2% (16 point approximation with non-uniform placement of points) to 0.8% - 1% for course alterations (Tables 2 and 3) and from 1.4% to 0.6% for speed reduction (Table 5).

5 SUMMARY AND CONCLUSIONS

In the course of simulation experiments that have been carried out and presented in this paper five polygonal approximations of ship domains have been tested. The tests included eight ship domain shapes and three types of encounter scenarios (head-on, crossing and overtaking). The results have shown that 8-point polygonal approximations can only give a rough idea of the collision avoidance manoeuvres performed for the original domains. The rise in precision of the approximation has been significant if the number of polygon's vertices has been increased from 8 to 16. The results that have been obtained for 16 points can be considered to be satisfactory, with the average errors being below 0.5 degree for course alteration manoeuvres and below 0.1 knot for speed reduction manoeuvres. The results have also indicated the superiority of non-uniform placement of approximation points (using more points on the fore and aft than on the sides). The progress that has been made when further increasing the number of points (from 16 to 32) was considerably smaller and therefore a 16-point solution has been considered to be the best choice for decision support systems applying ship domains of polygonal shapes or polygonal approximations of other shapes. Another conclusion is that any irregular domain shape, which uses more than those 16 points may be redundant to some extent. The extra points do not necessarily carry significant value in terms of their impact on the collision avoidance manoeuvres, though they certainly contribute to a higher overall computational time.

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