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Declarative ship domains in restricted areas

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Abstract

This paper presents the research results on declarative ship domains in restricted areas. The research was conducted for vessels of different sizes and speed relations. In order to determine the declarative ship domain, data were collected in the form of questionnaires. The influence of ship length and speed on the size and shape of its domain were analyzed. The detailed processes of data development and further approximation are shown. Declarative domains for ships of different sizes and speed relations are compared. As a result of the research, a mathematical model of a declarative ship domain showing the elliptical shape of the domain is presented. The intermediate and summary research results are presented and conclusions drawn.

Introduction

Ensuring safe navigation requires continuous analysis and assessment of the situation using all available navigational equipment of the ship. Assessment of the situation, and consequently identification a dangerous situation requires designation of the level of navigational safety, e.g. the value of navigational safety factor (Pietrzykowski & Wielgosz, 2011).

In the case of restricted areas, evaluation parameters commonly used in the situation analysis appear to be insufficient. Applying them in restricted areas is generally very difficult and requires a lot of experience in their interpretation and practical application. There is increasing discussion about the use of the ship's domain to analyze and assess the situation (Pietrzykowski & Uriasz, 2009; Pietrzykowski et al., 2011).

There are many existing ship domain definitions. The most often used is domain as an area around the ship, which navigators want to keep free of other objects (Goodwin, 1975).

Based on the above, it appears to be expedient to introduce a definition of declarative domain: declarative domain is an area or space that navigators declare that they want to keep free of other objects. There are several methods of determining the ship's domain. These include, among others, expert research conducted to determine the declarative domain.

The problem of determining the ship's domain is still valid because of the large number of factors affecting its shape and size. Such a large number of factors means that only some of them are considered in the process of domain determination. According to the experts, key factors are the size and speed of the vessel, and the type of water area.

Ship domain as a navigational safety criterion is of particular importance in the case of navigation in areas of high traffic density, where the vessel has limited maneuverability due to the existence of physical and legal restrictions. These are mainly the strait, areas of high maritime traffic density including areas with established traffic separation schemes.

In current and newly introduced navigational devices and systems it is possible to input the ship domain, and use it for:

- current analysis and assessment of the situation;
- planning the collision avoidance maneuvers;
- navigational decision support systems.

Due to the large variety of domains found in the literature, and differences in interpretation of domain boundaries, the author decided to determine three distinct domain boundaries effective for individual vessels. The following boundaries were determined: maximum, mean, and minimum.

Questionnaire research

In the process of analyzing the data relating to very specialized narrow fields of knowledge, acquisition of experts' knowledge is often used to perform research. In this process the expert navigators declare the limits of safety zones at three levels – minimum, mean, and maximum. Boundaries of safety zones determined in this way will be hereinafter referred to as the declarative ship domain.

The term "declarative domain" does not exist in the literature, but some domain definitions indicate their declarative nature (Wielgosz & Pietrzykowski, 2012).

In order to determine the declarative domains, research based on an expert questionnaire was conducted. The experts were the attendants of courses for the degree of Master Mariner and Chief Officer held in the Marine Officers Training Center at the Maritime University of Szczecin. The questions related to the ships passing distance, which navigators would keep during an anti-collision maneuver on selected relative bearings. Eight characteristic, easy to identify relative bearings were chosen for the questionnaire: 000°, 045°, 090°, 135°, 180°, 225°, 270°, 315°.

The research was conducted during eight aforementioned courses. A total of 153 questionnaires were collected, each containing three sets of declared distances at above-mentioned relative bearings for different ship sizes and speed relations. Finally, 459 individual ship domains for three ship sizes and different speed relations were collected. Calculations were carried out in nautical miles converted to meters, but also in relative distances units (a multiple of the individual vessel's length), where distances found in a questionnaire form were divided by the ship length.

As an area of research the author chose a restricted area well known to seafarers – Singapore Strait. A detailed, large scale navigational chart of the area was displayed by multimedia projector during questionnaire completion.

Questionnaire forms were prepared and research conducted for three ship sizes – large, medium, small (Table 1) and three different speed relations of own and target ship. The speed relations were described as follows:

- "high-low" means that own ship speed (proceeding "Full Ahead") is twice an much as target ship;
- "low-high" means that own ship speed is half that of target ship proceeding "Full Ahead";
- "equal" means that both own and target ship are proceeding with the same speed, which corresponds to "Half Ahead" setting.

Table 1. Particulars of the ships indicated in questionnaire forms

Parameter	Type and size of ship		
	Large	Medium	Small
	VLCC	LO-RO	River-sea ship
Length over all (L_{OA}) [m]	261.3	173.5	95.0
Breadth (B) [m]	48.0	23.0	13.0
Draft (T) [m]	9.0	8.1	3.7
Speed (v) [kn]	16.3	18.9	11.1

The collected questionnaires were processed and summarized:

- "maximum" is the highest value recorded on the selected relative bearing;
- "average" corresponds to the arithmetic mean of the values recorded on the selected relative bearing;
- "minimum" is the lowest value recorded on the selected relative bearing.

The collected data (series of points) were summarized in bulk charts in a so-called radar display, showing the (required) distance as a function of the angle of the relative bearing for all analyzed bearings (Figure 1). Both graphs and questionnaire forms were prepared in "head up" orientation (the ship's bow on top of the figure), making them clear and unambiguous for navigators.

After the initial linear approximation, three approximate domains were obtained for each analyzed vessel size and speed relationship (maximum, mean, and minimum). Predefined, selected declarative domains for a "Large" ship are shown in Figure 1.

The data collected in research were analyzed in two groups independently, analyzing the impact of the size and speed of the vessel on its declarative domain.

The predefined declarative domains described above were subject to an approximation. The approximation process was conducted for both absolute and relative domains. Because of the elliptical character of declarative domain data, the author decided to approximate using an ellipse.

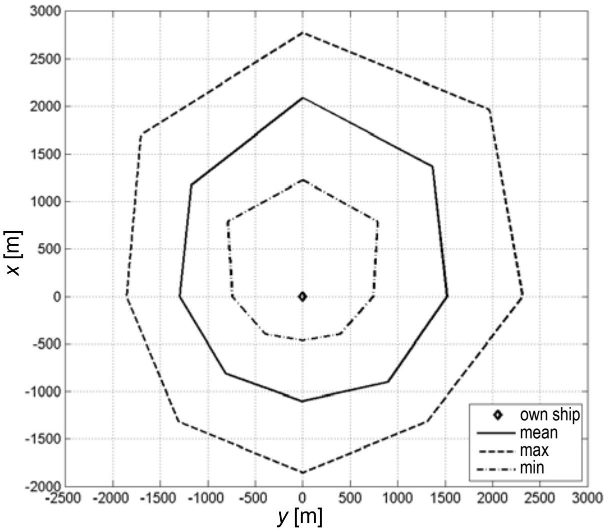

Figure 1. Pre-analyzed declarative domains – ship size "Large"

Approximation process

For the purpose of the approximation, a genetic algorithm was used. This is a tool for determination of a suboptimal solution – this means that the solution may not be optimal, but it is generally very close, often identical with the optimum (Goldberg, 2009).

The advantage is that, due to the method of selecting a solution from the group, the approximation runs much faster than a full search. The stop condition was set on achieving the minimum fitness function. For each domain, the cycle was repeated at least ten times with 100 iterations each time (100 generations).

The aim of the approximation was smoothing of the data and generating the four parameters of an ellipse: a, b, x_0, y_0, (Tables 2, 3, 4). Such ellipses are domains for vessels of the three analyzed sizes and three analyzed speed relations. In all cases, three domains were being approximated: maximum, medium, and minimum.

Both my own research and other sources show that the ship domain is of elliptical shape. The general form of an ellipse equation in parametric form is:

$$x(t) = x_0 + a\cos(t)\cos(\alpha) - b\sin(t)\sin(\alpha) \quad (1)$$

$$y(t) = y_0 + a\cos(t)\sin(\alpha) + b\sin(t)\cos(\alpha) \quad (2)$$

where:
a – major ellipse semi-axis;
b – minor ellipse semi-axis;
x_0 – displacement of the ellipse center on the X axis;
y_0 – displacement of the ellipse center on the Y axis;
α – angle of rotation of major ellipse axis.

Since in this case a rotation (inclination) of the major ellipse axis is not required (α = 0°), the equation becomes:

$$x(t) = x_0 + a\cos(t) \quad (3)$$

$$y(t) = y_0 + b\sin(t) \quad (4)$$

A block diagram of the approximation process is shown in Figure 2.

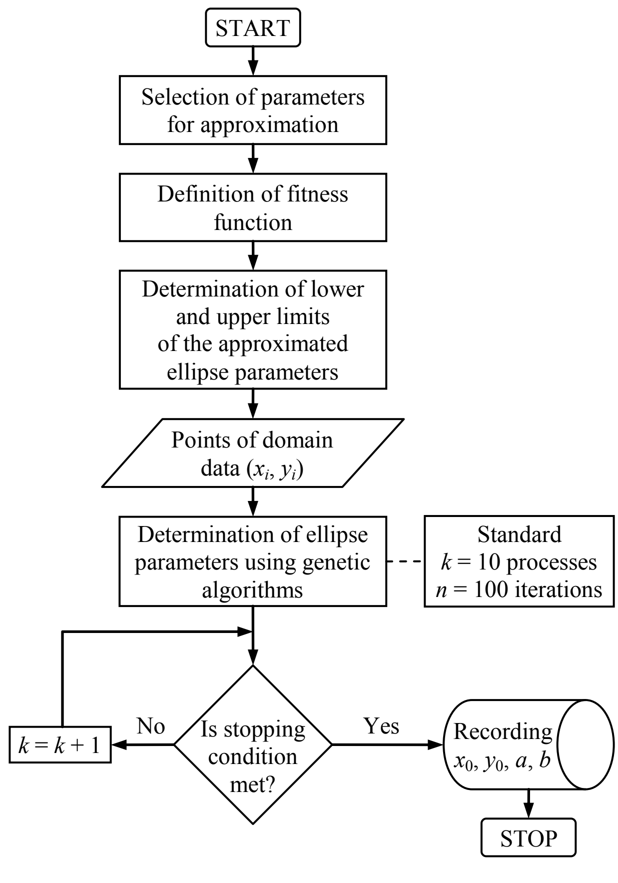

Figure 2. Process of approximation of domain parameters

The following four parameters of the ellipse (here considered as chromosomes) – a, b, x_0, y_0 form a genotype. As a measure of fitness, the author chose the sum of the distances between the domain boundaries (determined on the basis of declared data) and the estimated ellipse for the selected relative bearing. The best fitted was assumed to take that of minimum value of fitness function (5, 6). Relative bearings were analyzed with discretization 45°.

The fitness function thus becomes:

$$d = \min \sum_{i=0}^{n} d_i \quad (5)$$

$$d_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \quad (6)$$

where:

d – sum of distances for all analyzed relative bearings;

d_i – distance difference in the i relative bearing;

x_i – x coordinate of the approximated ellipse point;

x_0 – x coordinate recorded in selected relative bearing;

y_i – y coordinate of the approximated ellipse point;

y_0 – y coordinate recorded in selected relative bearing.

Generated in this way, basic ellipse parameters (a, b, x_0, y_0) enable plotting of researched domains of regular shape and performance of further analysis.

The declarative domains for ships of different sizes

Declarative domains for ships of different sizes were analyzed in the following categories: absolute and relative. An extract is presented below using an example of a “Large” ship.

The “Large” ship – absolute domains

The resulting approximated parameters of the absolute domains for “Large” ship are summarized in Table 2.

Table 2. Approximated parameters of the absolute domains for “Large” ship

Ship “Large”	x_0 [m]	y_0 [m]	a [m]	b [m]
Mean	532.52	200.02	1624.37	1476.52
Max	475.55	225.43	2315.26	2157.95
Min	370.54	0.99	853.00	869.22

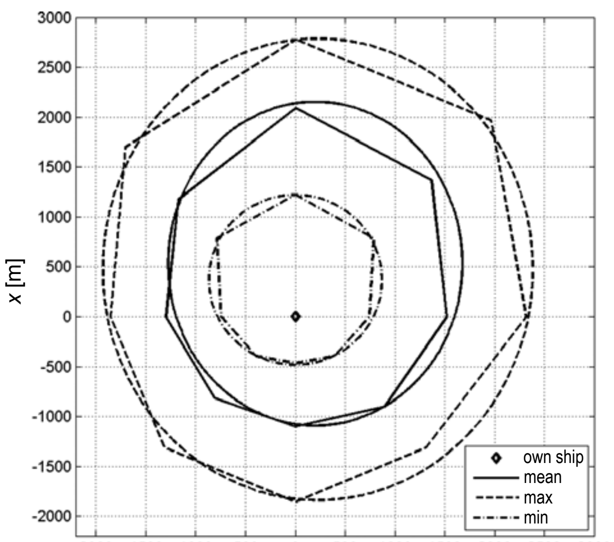

Figure 3. Approximated absolute domains for “Large” ship

Based on the data gathered in Table 2, absolute domains for “Large” ship were plotted and overlaid on the predefined declarative domains (Figure 3).

Comparison of real data with approximated data (Figure 3) confirms the legitimacy of the choice of the ellipse as the target figure in the process of declarative domain approximation. A relatively simple form of the ellipse equation allows us to make a simple mathematical description of the ship domain, facilitating further analysis.

The “Large” ship – relative domains

The use of the absolute values of domains expressed in meters or nautical miles is unambiguous and an easy way to use the navigational equipment and electronic systems. In practice however, navigators often also use relative values relating to the length of their own ship. Therefore, the author decided to present declarative domains both in absolute and relative units. There are two possible approaches in the process of determining relative domains:

1. dividing the approximated parameters by the corresponding length of the vessel;
2. dividing each individual distance per relative bearing (from the questionnaire) by the ship’s length, followed by independent approximation of each domain using genetic algorithms.

Both approaches should give similar results. It was recognized, however, that due to the fitness function formula, the second method would be more accurate. In addition, independent second path counting would help to identify any errors resulting from the processing of large amounts of similar data.

The resulting approximated parameters of the relative domains for a “Large” ship are summarized in Table 3.

Table 3. Approximated parameters of the relative domains for “Large” ship

Ship “Large”	x_0 [L]	y_0 [L]	a [L]	b [L]
Mean	2.038	0.565	6.216	5.651
Max	1.820	0.863	8.861	8.258
Min	1.418	0.004	3.264	3.327

Based on the data gathered in Table 3, relative domains for a “Large” ship were plotted and overlaid on the predefined declarative domains (Figure 4).

Relative domains obtained in this way have a very similar shape to the corresponding absolute domains, but the applied scale makes them more readable for some navigators.

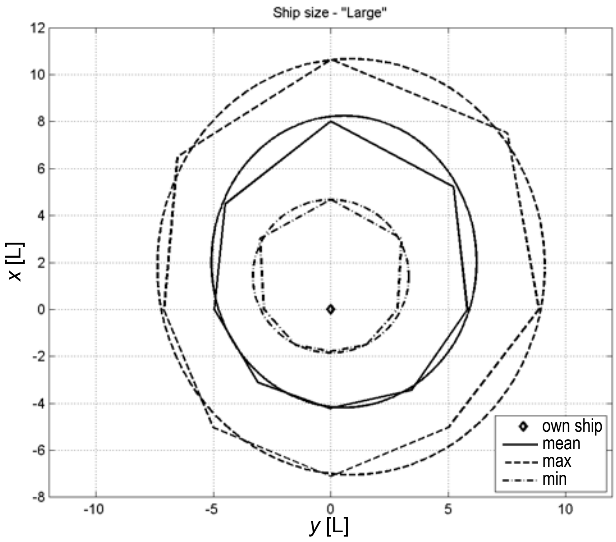

Figure 4. Relative domains after approximation – ship size "Large"

The declarative domains for ships in various speed relations

Research was conducted both for absolute and relative domains. In this paper, declarative domains for ships in different speed relations are described for the example of the speed relation "high-low".

The speed relation "high-low" – relative domains

Predefined relative domains show the visible elliptical nature of presented data, which allows also in this case using an approximation with an ellipse, using the same fitness function as before.

Parameters of approximated relative domains for "high-low" speed relation are shown in Table 4.

Table 4. Approximated parameters of the relative domains for "high-low" speed relation

Speed relation "high-low"	x_0 [L]	y_0 [L]	a [L]	b [L]
Mean	2.301	0.556	7.049	6.378
Max	3.110	0.887	12.889	11.927
Min	0.812	0.000	2.390	2.142

Based on the data gathered in Table 4, relative domains for the "high-low" speed relation were plotted and overlaid on the predefined declarative domains (Figure 5).

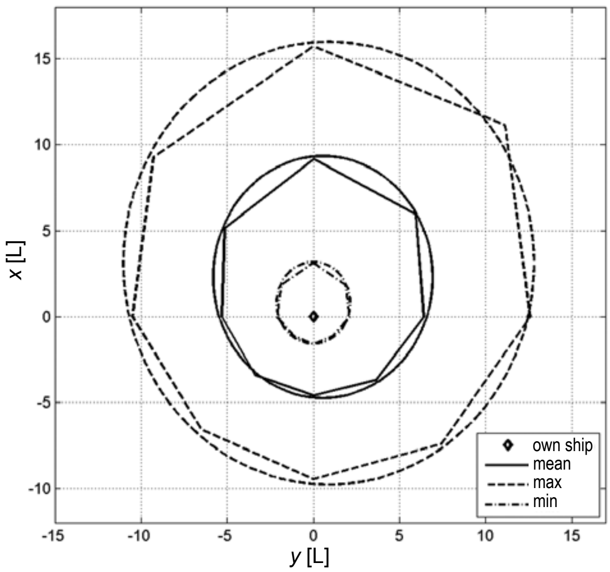

Figure 5. Approximated relative domains in speed relation "high-low"

The influence of ship's size and speed relations on declarative domain

A broad analysis of approximated domains was performed to determine the influence of ship size and speed relation in an encounter situation on its declarative domain.

Some of above-mentioned mean relative domains are shown in Figures 6 and 7 as an example. The figures show the regular shapes of domains, and the author will continue research to describe relations among them by mathematical equations.

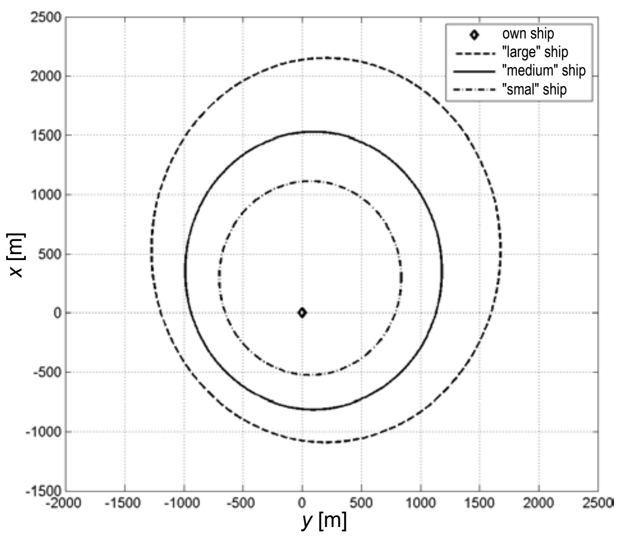

Figure 6. Absolute declarative mean domains for ships of different size

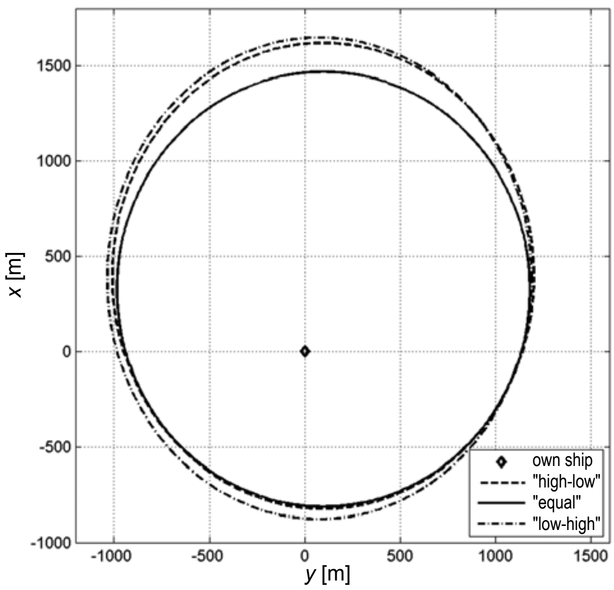

Figure 7. Declarative mean domains for ships in different speed relations

Conclusions

The research conducted allows the author to formulate the following conclusions:

1. A two-dimensional declarative ship domain can be described as an ellipse defined by four parameters: displacement of the center on the *X*-axis, displacement of the center on the *Y*-axis, the length of the major semi-axis of the ellipse, the length of the minor semi-axis of the ellipse.
2. The influence of the ship's size on the shape and size of its declarative domain is significant, and it is possible to describe with the four above-mentioned parameters as a function of the ship's size.
3. The influence of the ship's speed on the shape and size of declarative domain is significant, and it is possible to describe this relationship with the four above-mentioned parameters as a function of the ship's speed.
4. Due to the regular elliptical shape, there exists the possibility of formulating a mathematical formula for the domain based on the size and speed of the ship – this will be described in consecutive articles.
5. It is possible to apply the domain criterion for ships of every size and in all speed relations.

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