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Original article

The combination of analytical and statistical method to define polygonal ship domain and reflect human experiences in estimating dangerous area*

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Abstract

The paper suggests a new method of collision avoidance stemming from the concept of the polygonal target ship domain. Since the last century, we have witnessed the current typical ship domains classified and described. In this proposition, firstly, the domain is a geometrical manner which is used in both analytical and statistical method, resulting in the signification of practical application and simulation. Secondly, such domain will be applied to target ship under the combination of two separated parts: "Blocking area" and "Action area" in order to define the area where the ship must keep outside and how the actions to avoid collision can be generated. Thirdly, the concept has suggested the number of mathematical models for different approaching encounters, including head-on, overtaking and crossing situation. Finally, the parameters of turning circle of the ship can be proposed in determining the size of the domain. Statistical evidences indicate that this method reflects a crew's real habit and psychological in maneuvering. As the result, simple domain is shaped like imagination of sailors, but more accurate in calculating boundary. It promises an effective solution for automatic collision avoidance method. The next researches of this paper have achieved positive results in finding shortest route for avoiding collision. Moreover, while using statistical methods, classical researches face a serious problem in a wide application with different areas, this concept can make up a beneficial solution for the popular application. The numerous ship domains which are in previous researches will be carried out to compare and point out the simplification and effectiveness of the new method in practice.

*Keywords:*Ship domain, Blocking area, Action area, turning circle, advance distance of turning circle

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I.Introduction

Over the past decades, by analyzing the vital statistics of accidents at sea, it was irrefutable that the main reason of disaster derives from human factors. Over 80% of collision started from human's neglect and irresponsibility. Views on this issue vary from part to part. It is difficult to assume that an officer can keep watching every single second during all his shifts. The necessity of the automatic collision avoidance system, therefore, became the biggest challenge to scholars over the world, especially when the marine transportation has been developing day by day and altering to the core of international trade. The ship domain has been known as the dramatically effective method for this system in order to estimate the risk of collision (CR) and to define the dangerous area around the ship. Historically, the first domain has been known as a shape of the circle of which the center will be placed at the ship's position. Such circle is the main factor for calculating the distance of the closest point of approach (DCPA) and the time remaining to reach this point (TCPA), which are two parameters used effectively in estimating CR and making a decision of avoiding collision. Obviously, the terms DCPA and TCPA are more concerned and commonly used. In addition, to develop the ship domain, Fujii (Fujii, 1971) introduced an ellipse domain and Goodwin (Goodwin, 1975) proposed three segments of the circles created by different radius, not to mention the fact that both of them have been widely applied since the 1970s in marine traffic engineering. The following step can be illustrated briefly by numerous researches of: Davis et al. (1980, 1982); Coldwell (1983); Zhao et al. (1993), Zhu et al. (2001), Smierzchalski (2001), Kijima and Furukawa (2001, 2003), Pietrzykowski (2004, 2006, 2008), Szlapczynski (2006), etc. The existing domains have presented various shapes and sizes taking into account of different factors. Those which are considered in determining the parameters of ship domain can be listed as ship size, ship's maneuvering characteristic, sea state, hydrological conditions, meteorological conditions, ship's velocity, relative ship's speed, traffic intensity, the knowledge of navigator, the factors – related variety make the definition of ship domain complex. On the whole, the previous researches were divided into two trends due to the function of domain: the first one requires the dangerous area that other vessels have to keep clear and the second plays vital role in risk assessment. This paper introduces a new concept of the ship domain, including two parts: "Blocking area" and "Action area", besides, the first function mentioned is considered, the second function is really removed and replaced by using DCPA and TCPA. Additionally, the methods of determination and configuration of the domain will be analytically described in order to point out the advantage of such methods.

II. Previous ship domain

The concepts of ship domain were described early from the 1960s and altered to one of the most attractive potential fields, proved by numerous researches over the past 50 years. The advantages of ship domain include quickly identifying and evaluating the navigation situation. Apparently, it plays a key role in assessing CR and generating the decision of the maneuver. The previous studies have been distinguished into three groups, containing statistical, analysis and artificial intelligence methods.

Firstly, the statistical method uses the data resigned from the ship's position and trajectories in order to find the area around the ship where other objects need to keep outside. In the case of Goodwin, his model also was determined from a great number of records and simulated data. The parameters of Goodwin's model are D_f = 0.85 NM, D_p= 0.7 NM, D_a = 0.45 NM and the recommended sea zone is the North Sea. Coldwell's model is separated by head-on model and over talking model, the parameters of them are D_f = 6.1L, D_p= 1.75L, D_s = 3.25 L and D_f = 6.0L, D_p= D_a = 1.75L. The statistical data was collected from three zones (Zone A, Zone B, Zone C) and introduced in his research. Furthermore, there are many other studies using this method, especially Fujii and Davis's model.

Secondly, the analytical method uses various variables in describing the calculation of the factor to create domain boundary, in particular, they are ship's speed, relative speed, geometrical dimensions, etc. The Wawruch's study (Wawruch, 1998) suggested an analytical description of domain. The next steps are the researches of Smierzchalski, R. and Weintrit, A. (1999) getting more attention by a hexagonal domain depending on dynamical length, width and speed of the ship. Through analyzing the variables, this method will specify accurately the domain boundary and bring it in wide application. Notwithstanding, the human factors have not been included and the researchers have to make a choice to get some important variables among those mentioned above.

Thirdly, the artificial intelligence method (AI) offers more benefit than others in representing the knowledge of navigator caused by the simulation of expert knowledge. This work has been effectively exercised by supporting tools. The most substantial tools mentioned are fuzzy logic and artificial neural networks. The first application of fuzzy logic in determining domain is James's study (James, 1986) followed by Zhao et al. (1993) and Sheng et al. (2007). The method has potential in defining ship domain by taking into account various factors. The multi-membership functions can be created by using various linguistic variables, giving rise to the effective description of domain wished by human whereas the assessment of effective domain will not be described.

Besides, the ship domain can be classified by the shape of boundary which can be illustrated briefly by circular proposed in the studies of Goodwin (1975), Davis (1980, 1982), Zhao et al. (1993), Zhu (2011), Sheng et al. (2007); elliptical proposed in the studies of Fujii (1971), Coldwell (1983), Kijima (2001, 2003) and polygonal domain proposed in the studies of Smierzchalski (2001, 2003), Pietrzykowski (2004, 2006). The fact of the matter is that it is inestimable to assess what shape is the most effective by virtue of the different determining purposes. There are two researches in numerous configurations which are known mostly in determining the domain by two areas. Typically, the model of Kijima suggested the combinations of two ellipses which define the area into "Blocking area" or "Watching area", while the Davis's domain was modeled by two circles. Without the shapes and functions of the areas, they are constantly understood as the ship domain area and the ship's area.

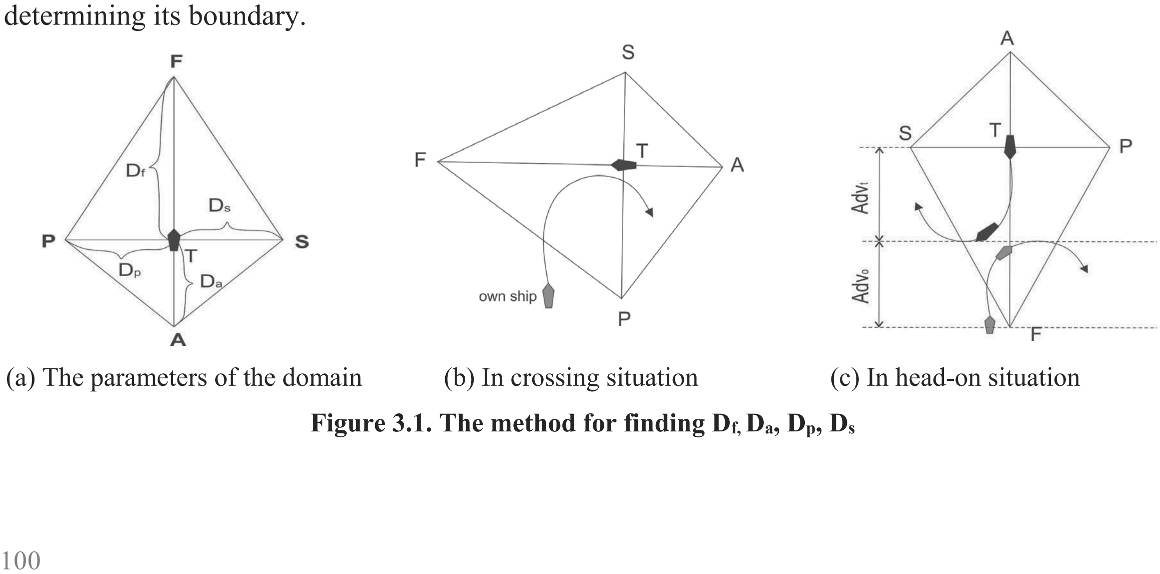
Finally, compared with previous studies, this concept is the combination of two methods: statistical and analytical with the advantage of each one. The statistical method may be seen as the most effective way to determine the ship domain, however, it is required to contain future results because of the changing data related to the changing navigation situation of the examined area. In addition, it is difficult to apply the statistical model in most of the seas due to the difference of navigational considerations. This paper uses statistical method in difficult way and develops to the wide application in many regions. As mentioned, the analytical method does not include human factors, even so this paper introduces a formula for determining boundaries of the domain reflecting the habit of navigator in maneuvering. In the configuration, the model of this paper consists of firstly, “Blocking area” - quadrilateral and secondly “Action area” – circular shape. Apparently, the “Blocking area” which is the water around the target ship seems to be the most dangerous area that the ship has to keep outside firmly and “Action area” requires the distance that the ship must give actions for resolving the dangerous encountering situation.

III. Mathematical description of “Blocking area”

3.1. “Blocking area”

If a CR exists between two ships underway, an action will be generated as soon as possible under the international or domestic rules at sea. It gives a question for the safe passing distance between two vessels mentioned. This paper will propose a method for determining the shape of the target ship domain, such as the recommendation of shortest distance for passing performance. D_f, D_a, D_p and D_s in figure 3.1 determine the dangerous distance at fore, astern, port side and starboard side respectively. The equation for calculating these parameters depends on which situation that two ships are meeting.

An officer surely knows that his vessel should proceed at a safe speed at all time of the maneuver. He can take effective action in order to avoid collision and can stop within an appropriate distance in significantly dangerous situations (COLREG 72). This distance may be safe so that the ship can be stopped at the benefit position for preventing collisions. However, considering the human psychology, when the most dangerous encountering situation is coming, the officer frequently commands “Hard port” or “Hard starboard”. This is the main reason for the advance distance of turning circles of the target ship and own ship which become the first and second important variable in order to identify the dangerous area around the target ship (Adv_t and Adv_o separately). The figure 3.1 introduces the “Blocking area” of the domain and the concept in determining its boundary.



(a) The parameters of the domain (b) In crossing situation (c) In head-on situation

Figure 3.1. The method for finding D_f, D_a, D_p, D_s

Naturally, human being tends to distinguish the dangerous area around the target ship by his ship's maneuvering characteristics. Specifically, the turning circle is always the first standard factor referred to, which becomes the habit of navigator. However, this competence is only useful in crossing situation or avoiding the non-moving object. In head-on situation, when the relative speed is high and there is no target ship's turning circle, the navigator cannot define the dangerous distance ahead. As a result, he has to avoid target ship at the longer distance. The concept of this paper is generating ship domain which depends on the advance distance parameter of turning circle. In order to apply this model in all of the conventional situations, the Adv_t parameter is needed to determine. This work will be implemented in the next part after defining the formula "Blocking area" as proposed as the following:

The head-on situation:

$$\begin{cases} D_f = Adv_o + Adv_t + ErrGPS + \Delta \\ D_s = D_p = D_a = kL_t + ErrGPS \end{cases} \quad (1)$$

In crossing situation:

$$\begin{cases} D_f = Adv_t + ErrGPS + \Delta \\ D_p = Adv_o + ErrGPS \\ D_s = D_a = kL_t + ErrGPS \end{cases} \quad (2)$$

In over-taking situation, the equation is:

$$\begin{cases} D_f = Adv_t + ErrGPS + \Delta \\ D_s = D_p = D_a = kL_t + ErrGPS \end{cases} \quad (3)$$

Where:

- Δ is denoted as the maximum error of regression implements in calculating the advance distance of the target ship's turning circle.
- ErrGPS is sources of range error in Global Positioning System.
- *K* is coefficient ratio of safe passing distance.
- L_t is length of the ship.
- Adv_o=constant

Sources of range error in Global Positioning System constant signal arrival C/A: ±3m, Signal arrival P(Y): ±0.3m, Ionospheric effects: ±5m, Ephemeris errors: ±2.5m, Satellite clock errors: ±2m, Multipath distortion: ±1m, except the Ionospheric effects: ±5m, total error from GPS is 9.3m (ErrGPS).

3.2. The safe passing distance

The mentioned equations of "Blocking area" include three issues needed to be cleared: target ship's advance distance of turning circle (Adv_t), the co-efficient ratio of the safe passing distance (*k*) and the maximum error of regression implements (Δ). The shortest distance for the passing safety between two vessels (MinPD) is represented by kL_t:

$$MinPD = kL_t \quad (4)$$

An inspection was implemented from 61 officers working on board to find co-efficient ratio *k*. The MinPD value can be understood as minCPA set on the radar without passing encounter's heading line.

Table 1: The examination of MinPD

No.	POSITION	SHIP NAME	SHIP TYPE	LPP(m)	MinPD(m)
1	Second officer	Comatce star, IMO:9119189	Bulk Carrier	143	480
2	Third officer	Pacific Express, IMO: 9167851	Container	119	450
3	Second officer	Ten Yoshi Maru,IMO: 9520912	Bulk Carrier	185.6	926
4	Third officer	King Island, IMO: 9583017	Bulk Carrier	186.2	740
5	Second officer	Tan Binh 135, IMO: 9253404	Bulk Carrier	160.4	530

Source: Marine Department (2013); MOT (2014)

It is statistically evident that the MinPD is around 2.8 to 4.6 times of ship's length and the average result is k=3.63. To compare this value with other researches:

- The first, Coldwell' head-on model is defined by semi-major axis (D_f) = 6.1L and minor axis (D_p + D_s) = 5.0L, where D_p = 1.75L and D_s = 3.25L. Visually, $D_s \approx$ MinPD (0.43L smaller than inspected value). These parameters were concluded in his examination of A Zone which is relatively open waters, an analysis more suitable for open water; 3.25L, therefore, it can be seen as the smallest distance for the passing actions in open sea.
- The restricted distance of the beam is taken into account for another kind of domain known as bumper model in Theory and Practice of ship handling book, by Inoue, K., Professor Emeritus, Kobe University (2012, p.180). Such model suggested the assessment of collision-risk in congested waters and applied extensively for route-planning purpose due to its simplicity and explicitness. The domain includes 2 parts separated by the traverse axis of the ship. It ranges from 8 ship lengths fore and aft (D_f = 6.4L and D_a = 1.6L) and 3.2 ship lengths from port and starboard centered on one's own ship (D_s = D_p = 1.6L). These parameters will be increased two to three times as recommended when maneuvering in open sea, which means that D_s = D_p = 3.2L to 4.8L (the stern-part is 3.2L to 4.8). The inspection value (3.63L) of this paper is in this range.
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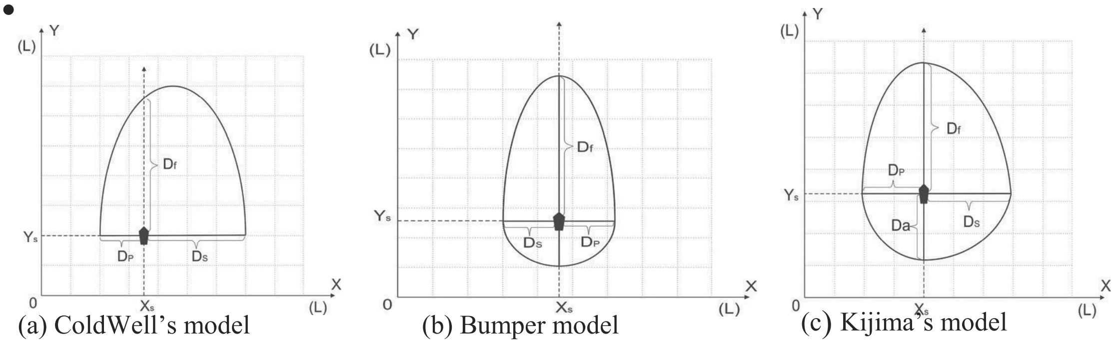


(a) ColdWell's model (b) Bumper model (c) Kijima's model

Figure 3.2.Safety passing distances of other models

- The work of Kijima (Kijima,2003) introduced an equation to calculate longitudinal and lateral radii of the domain which is shown below:

$$\begin{cases} R_{force} = D_f = (1+1.34\sqrt{k_{AD}^2 + (k_{DT}/2)^2}L \\ R_{aft} = D_a = (1+0.67\sqrt{k_{AD}^2 + (k_{DT}/2)^2}L \\ R_{starb} = D_s = (0.2+k_{DT})L \\ R_{port} = D_s = (0.2+0.75k_{DT})L \end{cases} \quad (5)$$

Where L is the own ship length, k_{AD} and k_{DT} are represent gains of the advance distance of turning circle AD and the tactical diameter DT respectively can be calculated as follows:

$$\begin{cases} k_{DT} = D_T / L = 10^{0.5441\lg V_{own} + 0.0795} \\ k_{AD} = A_D / L = 10^{0.3591\lg V_{own} + 0.0952} \end{cases} \quad (6)$$

Where: V_{own} is own ship's speed (knots)

A comparison table is given under the survey of 100 vessels point out the differences of the safe passing distance between Kijima's equation and the result of inspection mentioned.

Table 2: The difference of the safe passing distance between two models

No.	Ship name	Lpp	Advance	Tactical diameter	MinPD	D_s'	D_p'	ΔD_s	ΔD_p
1	Van Don ACE	100	360	400	363	420	320	-57	43
2	Pacific Express	119	425	450.2	431.97	474	361.45	-42.03	70.52
3	Tan Binh 135	160.4	500	490	582.25	522.08	399.58	60.172	182.672
4	Ten YoshiMaru	185.6	648.2	740.8	673.7	777.92	592.72	-104.192	81.008
5	Ikan Tamban	132	500	500	479.16	526.4	401.4	-47.24	77.76
6	Northern Star	100	360	370	363	390	297.5	-27	65.5
7	Morning Viship	1105.5	344	360	382.96	381.1	291.1	1.865	91.86

The model of Kijima gives two parameters Ds' and Dp', herein we only focus on Ds' as the longer distance for passing.

$$\begin{cases} MinPD = 3.63L \\ \Delta D_s = MinPD - D_s^{'} \end{cases} \quad (7)$$

The average value is determined approximately 79.7275 (m). Evidently, the error comparing between two models is trivial leading to the trustworthy result.

In the nutshell, the first work is finished in finding the most important parameter used to determine the boundary of the model (*k*). The statistical method was implemented without the assessment of navigational condition. The criterion is navigator's knowledge according to the ship's size which causes the discouraging application in the disadvantageous navigation situation. In general, when the vessel is on the way in bad situations such as bad weather, restricted maneuvering ability, restricted visibility, etc., the duty officer has to change the operation to manual control. As a result, the purpose of this concept makes up a domain for the normally navigational condition. As mentioned, in the next step, the work of defining a second variable (Adv_t) will be considered by a similar condition.

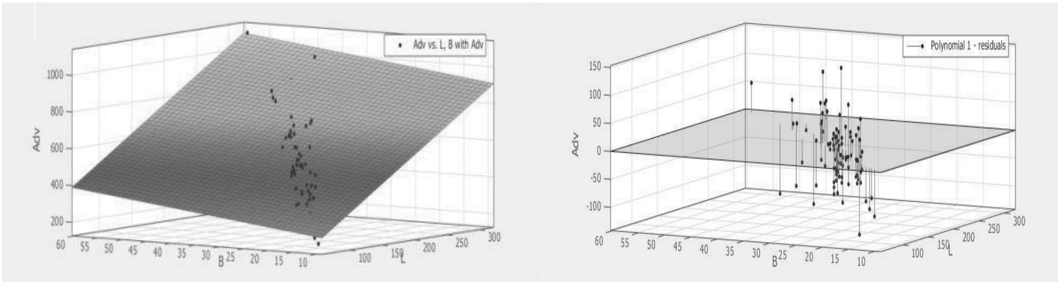
3.3. The Advance distance of the target ship's turning circle

In order to get a correlation between the advance distance of turning circle and ship's structure, the suggested method is the linear regression. As noted, the area of danger around the target ship will be computed, using Adv_t, Adv_o and L_t, while Adv_o and L_t can be respectively reached by own ship's maneuvering characteristics and AIS (automatic identification system). As consequence, the main work is finding Adv_t. Of course, it is not an easy task. In the future, it needs more researches on this issue rather than what is given in this paper. However, the determination of this parameter is given in this paper by using liner regression method and conditions assumed to be normal (no wind, no flow, conventional propeller type, etc.). Statistical number of vessels is nearly 100 cargo ships. Future work should split and identify each type of ship and propeller categories to apply to each specific case. This database can be generated to 150-200 vessels in order to see the visual test result more clearly.

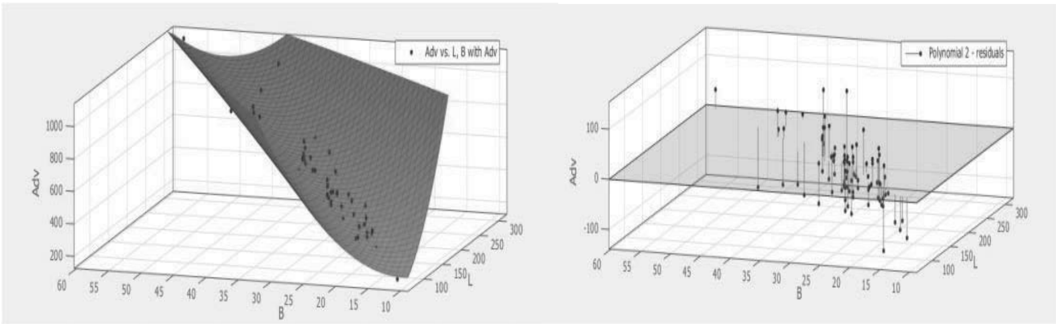
Table 3: DATA resource

No.	Ship infomation	Condition	Displacement (MT)	LOA	Lpp	B	Depth	Cb	L/B	Initial speed	Advance (m)	Transfer (m)	Tactical diameter
1	Pacific Express IMO: 9167851	full load	14052	128.53	119	22.4	11.2	0.54	5.31	16	425	208	450.2
2	King Island,IMO: 9583017,	full load	67812	189.99	186.2	32.296	18.018	0.61	5.77	14.3	756.3		724.2
3	MV VIET PHU 09 OPEN HAI	full load	3023.8	74.7	70	11.2	4.75	0.79	6.25	12	172		192
4	COMATCE STAR, Vietnam,	full load	28732	150.52	143	26	9.544	0.79	5.50	11	420.6	228.6	473.96
5	OCEANUS 08,	full load	6139	96.51	89.5	16.4	5.15	0.79	5.46	11.5	304.8	129.54	274.32
6	AN PHU 16, imo: 9561681	Full load	7403.4	97.28	90.56	15.6	6.75	0.65	5.81	10	315	135	333.4

Conclusions will be shown after analyzing the relationship between the 3 columns (L_{pp}, B, Advance) based on regression coefficients through a significant test.



(a) Linear model 1



(b) Linear model 2

Figure 3.3. Curve fitting of Advance parameter

The polynomial regressions were found

Linear model Poly1:

f(x,y) = 23.83 + 2.531*x + 4.062*y

Goodness of fit:

SSE: 2.496e+05

R-square: 0.903

Adjusted R-square: 0.901

RMSE: 50.99

Linear model Poly2:

f(x,y) = -44.87 + 3.815*x + 2.096*y + 0.05298*x^2 – 0.6822*x*y + 2.066*y^2

Goodness of fit:

SSE: 2.394e+05

R-square: 0.907

Adjusted R-square: 0.902

RMSE: 50.74

Overall, the figures indicate that Linear model 2 can be chosen for estimating Advance distance of the target ship's turning circle, however, the difference of the results calculated by two equations is really small leading to the fact that the equation 1 can be used for a simple calculation.

$$Adv_t = 2.531L_t + 4.062B_t + 23.83 \quad (8)$$

or:

$$Adv_t = 3.815L_t + 2.096B_t + 0.05298L_t^2 - 0.6822L_tB_t + 2.066B_t^2 \quad (9)$$

Where, L_t = *length of target ship (m)*

B_t= *breadth of target ship (m)*

3.4. The maximum error of regression implements

The forecasting variable (known as ŷi) is close to the data set (collectively known as y_i), however, the range of error ŷi - y_i is maximum at nearly 146.376 m and 158 m in Eq.8 and Eq.9 respectively. This value will be changed when the input variable in table DATA resource increases. For safety, predicted variable should be higher than the data sets.

$$\Delta = \max_{0 \le i \le n} \sqrt{(\hat{y}i - yi)^2} \qquad (10)$$

IV.Mathematical description of "Action area"

The other evaluating CR systems can find out the encounters in 5 miles diameter. However, too early action in many cases is meaningless due to the newly changed course of target ship for a new route in the voyage. This study suggests a circle defining the distance for the action (CAA). The radius of CAA is calculated by the following:

$$R_{CAA} = D_f + 0.167 \times V_{relative} \qquad (11)$$

In general, navigators define that the safety range for avoiding other vessels depends on the size of target ships and typically is 2NM in normal conditions by their habit. This experience sometimes does not reflect correctly in practice. One may have to think about two vessels in a head-on situation with both 15 knots in velocity, TCPA calculated is 4 minutes. This situation will cause a fear to navigators it is suggested that the TCPA varying from 6 to 10 minutes is a good time for an action. The CEA must guarantee that the action has to be activated neither too early nor lately. The center of CAA will be placed in the target ship's position.

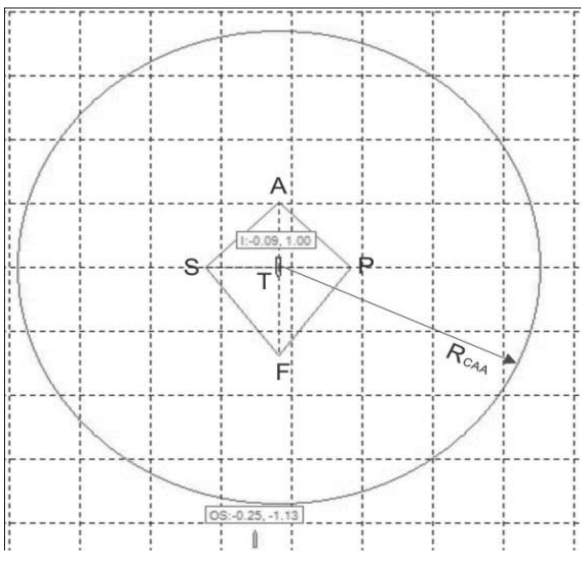


Figure 4.1. The circle of estimating action

V. Conclusions

The variety of ship domains have been described and classified into three major methods and different configurations. According to the classifications, this paper suggests the mathematical descriptions of ship domain for each encountering situations in accordance with human habits. The statistical method is applied in order to establish the defining equation of advance distance of turning circle for various ships by the numerous statistical data. Once this parameter is defined, it will be then applied in the formulated analytical formulas, consequent of wide application related to calculating ship domain in every area. This paper makes up the satisfactory solution by collecting almost of advantages from three methods in determining ship domain. Furthermore, the simple shape of the "Blocking area" can lead to the significant simulation and the "Action area" can recommend the effective distance for taking action to keep own ship clear outside target ship's "blocking area". The future works are planned to raise the amount of ship data used in calculating Adv_t and k from 100 to 300 for the convincing conclusion and the simulation program will be adequately implemented by the automatic collision avoidance algorithm using the proposed domain. This simulation promises valuable result which would be introduced in foreseeable future.

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