AN EMPIRICAL MODEL OF SHIP DOMAIN
FOR NAVIGATION IN RESTRICTED WATERS

WANG YUE YING
(B.Eng. in CE, 
Dalian University of Technology)

A THESIS SUBMITTED
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
DEPARTMENT OF CIVIL AND ENVIRONMENTAL
ENGINEERING
NATIONAL UNIVERSITY OF SINGAPORE
2012
DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirely.

I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

Wang Yue Ying
20 August 2012
ACKNOWLEDGEMENTS

The past four years of study in the National University of Singapore is a journey full of challenges from my research work as well as a journey of self-discovery. Upon the end of this journey, I am deeply grateful to all the people who have accompanied me through the years.

Firstly, I would like to express my deepest gratitude to my supervisor, Associate Professor Chin Hoong Chor for his continuous support and encouragement, constructive advices and patient guidance throughout my PhD study. His instruction and constant motivating power have helped me to overcome the difficulties and challenges throughout the study. In addition to teaching me the way of researching, he played a more important role as a mentor who helped me discover my strengths and limitations.

I am also grateful to Professor Quek Ser Tong, Associate Professor Meng Qiang, and Professor Choo Yoo Sang for their invaluable suggestions during my qualifying examination and oral defense. In addition, I wish to thank my module lecturers and professors in NUS: Professor Fwa Tien Fang, A/P Lee Der Horng, A/P Chan Weng Tat, Prof. Ong Say Leong, and A/P Szeto Wai Yuen.

I owe my sincere gratitude to National University of Singapore for offer me tuition-waiver scholarship and China Scholarship Council for supporting me on the living expenditure for the entire period of studying.
I am deeply grateful to Maritime and Port Authority of Singapore for providing the VTIS data for my research work. I will also thank many captains and marine experts for advising me with their expert judgments including Capt. Gopala, Mark, Capt. Peter, Capt. Jose, and Capt. T.C. Jong.

I am greatly indebted to the technicians in the traffic laboratory Mdm. Yu-Ng Chin Hoe, Mdm. Yap-Chong Wei Leng, Mr. Foo Chee Kiong for their continuous support and considerate cares to me during my study.

I would like to thank all my colleagues and friends, namely Shimul, Ashim, Hung, Zhenbang, Habib, Qui, Zhengyi, Hongyu, Zhanglei, Fenghua for their cares and encouragement in these four years.

Finally, I would like to extend my special thanks to my beloved parents, who have ever backed me up and assured me. Because of you, I was able to journey so far.

Wang Yue Ying

August, 2012
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SUMMARY

As a principal criterion for navigational safety, the concept of ship domain plays an important role in marine traffic engineering. Ship domain has been widely used in risk assessment, collision avoidance and path planning for navigation. Despite several decades of research, there are still issues on ship domain that are not well understood. These include how the ship domain is described (i.e., size and shape); what factors influence the domain; how the use of domain affect rules of encounter and how it is applied in path planning. Moreover, many of the previous models of ship domain assume a deterministic representation and are derived theoretically without empirical support. Ship domain is likely to be stochastic in nature, dynamic in usage and interactive in application. The objective of this research is to develop an empirically-established stochastic model of ship domain that accounts for dynamic interaction between vessels and can be effectively applied to path planning in navigation within restricted waters.

Following a critical review of literature on the concept of ship domain and how it has been represented, measured and modeled, a new approach of modeling ship domain separately around each ship is proposed. The formulated mathematical model is then calibrated using seven hours of vessel movements within the Singapore Port under both day and night conditions. By restructuring the traffic movement to ship encounters, the set of ship location and movement data associated with close encounters are used to calibrate the ship domain characterized by ship attributes, i.e., overall length, speed, relative bearing and heading difference. The calibration process is performed iteratively between the basic ship domain representing that around a stationary ship and a speed function for the contingent set
of close encounters which are dependent on the calibrated ship domain. The results show that the ship domain is neither elliptical nor symmetrical and thus it is best to adopt a segmented polygonal shape to account for the mathematically ill-defined shape. Moreover calibrations also suggest that nighttime domain is more sensitive to changes in sailing speed than the daytime domain, and navigators tend to be more conservative in nighttime navigation. Furthermore, by introducing a non-dimensional stochastic element in the model, the variation in the domain size which may account for variation in human perception of ship domain among navigators can be derived.

The proposed ship domain has been applied in studying hypothetical two-ship encounters to solve collision-avoidance problem in a close range. As an extension, the ship domain is used to model optimal navigational paths for multi-ship movements in a realistic situation of the Singapore Port. The path planning is achieved by optimizing paths based on multiple objectives, i.e., maximizing navigational safety, minimizing cost in travel distance and time, maximizing path smoothness and satisfying time window constraints and operational requirement of ships. The two case studies serving as illustrations, well demonstrate the dynamic and interactive effect of applying the ship domains on multiple ships and that path planning can be modeled effectively with the proposed ship domain model.

In summary, this study has provided a better understanding of spatial separation of ships when navigating in restricted waters. The study shows that such interactions of ships can be modeled interactively by using a ship domain in path planning that account for stochastic uncertainties and dynamic update of movements.
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<th>Description</th>
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<tbody>
<tr>
<td>AIS</td>
<td>Automatic Identification Systems</td>
</tr>
<tr>
<td>ARPA</td>
<td>Automatic Radar Plotting Aid</td>
</tr>
<tr>
<td>COLREGS</td>
<td>International Regulations for Preventing Collisions at Sea</td>
</tr>
<tr>
<td>CPA</td>
<td>Closest Point of Approach</td>
</tr>
<tr>
<td>DCPA</td>
<td>Distance at Closest Point of Approach</td>
</tr>
<tr>
<td>ECDIS</td>
<td>Electronic Chart Display and Information System</td>
</tr>
<tr>
<td>ENC</td>
<td>Electronic Navigational Charts</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GW</td>
<td>Give Way</td>
</tr>
<tr>
<td>HO</td>
<td>Head On</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>LOA</td>
<td>Length Overall</td>
</tr>
<tr>
<td>MMSI</td>
<td>Maritime Mobile Service Identity</td>
</tr>
<tr>
<td>NP</td>
<td>Navigational Path</td>
</tr>
<tr>
<td>OD</td>
<td>Origin-Destination</td>
</tr>
<tr>
<td>OS</td>
<td>Own Ship</td>
</tr>
<tr>
<td>OT</td>
<td>Overtaking/Overtaken</td>
</tr>
<tr>
<td>RR</td>
<td>Range Rate</td>
</tr>
<tr>
<td>SAR</td>
<td>Search and Rescue</td>
</tr>
<tr>
<td>SO</td>
<td>Stand On</td>
</tr>
<tr>
<td>SP</td>
<td>Safe Passing</td>
</tr>
<tr>
<td>STW</td>
<td>Speed Through Water</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>TCPA</td>
<td>Time to Closest Point of Approach</td>
</tr>
<tr>
<td>TS</td>
<td>Target Ship</td>
</tr>
<tr>
<td>TSS</td>
<td>Traffic Separation Scheme</td>
</tr>
<tr>
<td>UKC</td>
<td>Underkeel Clearance</td>
</tr>
<tr>
<td>VLCC</td>
<td>Very Large Crude Carriers</td>
</tr>
<tr>
<td>VTIS</td>
<td>Vessel Traffic Information System</td>
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<thead>
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<th>Description</th>
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<tbody>
<tr>
<td>$%\ E$</td>
<td>Error percentage</td>
</tr>
<tr>
<td>$AT\ (p)$</td>
<td>The arrival time of path $p$</td>
</tr>
<tr>
<td>$C_{\text{static}}$</td>
<td>Set of static constraints</td>
</tr>
<tr>
<td>$cl_j$</td>
<td>Penalty cost related to the channel limit $j$ for ship in segment</td>
</tr>
<tr>
<td>$\text{Comfort}\ (p)$</td>
<td>Comfort consideration for path $p$</td>
</tr>
<tr>
<td>$d_{o,t}$</td>
<td>Distance between the OS and TS</td>
</tr>
<tr>
<td>$DCPA_{\text{lim}}$</td>
<td>Limiting value of DCPA</td>
</tr>
<tr>
<td>$\text{Dist}\ (p)$</td>
<td>Total travel distance for path $p$</td>
</tr>
<tr>
<td>$D_T$</td>
<td>Tactical diameter of a ship</td>
</tr>
<tr>
<td>$E$</td>
<td>The error defined as the difference between modeled domain and the distance between ship pair</td>
</tr>
<tr>
<td>$\text{Economy}\ (p)$</td>
<td>Economy consideration for path $p$</td>
</tr>
<tr>
<td>$E_{\text{os}}$</td>
<td>Error due to OS</td>
</tr>
<tr>
<td>$E_{\text{ts}}$</td>
<td>Error due to TS</td>
</tr>
<tr>
<td>$E_{\text{rel}}$</td>
<td>Relative error</td>
</tr>
<tr>
<td>$\text{Fitness}\ (p)$</td>
<td>Fitness function for path $p$</td>
</tr>
<tr>
<td>$F_n$</td>
<td>The objective function of the optimization problem for estimating parameters</td>
</tr>
<tr>
<td>$\text{Fuel}\ (p)$</td>
<td>Path smoothness for path $p$</td>
</tr>
<tr>
<td>$g(v)$</td>
<td>Speed function in the ship domain model</td>
</tr>
<tr>
<td>$G_c$</td>
<td>Safety cost of a collision</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$G_{ci}$</td>
<td>The penalty value related to the encroachment to channel limit</td>
</tr>
<tr>
<td>$gene(s_i)$</td>
<td>Representative gene in the Genetic Algorithm defined by a set of points $s_i$</td>
</tr>
<tr>
<td>$g_f(v)$</td>
<td>The speed function for the fore side</td>
</tr>
<tr>
<td>$g_a(v)$</td>
<td>The speed function for the aft side</td>
</tr>
<tr>
<td>$g_p(v)$</td>
<td>The speed function for the port side</td>
</tr>
<tr>
<td>$g_s(v)$</td>
<td>The speed function for the starboard side</td>
</tr>
<tr>
<td>$m$</td>
<td>The sign values in defining the speed function</td>
</tr>
<tr>
<td>$n$</td>
<td>The sign values in defining the speed function</td>
</tr>
<tr>
<td>$n_{SE}$</td>
<td>Sample size of close encounters</td>
</tr>
<tr>
<td>$N()$</td>
<td>The amount of encounters satisfying the condition in bracket</td>
</tr>
<tr>
<td>$L$</td>
<td>Ship Length Overall (LOA)</td>
</tr>
<tr>
<td>$l_i$</td>
<td>Length of segment $i$</td>
</tr>
<tr>
<td>$l_{sd,k}$</td>
<td>The side line of the TSS zone $k$</td>
</tr>
<tr>
<td>$l_{st,k}$</td>
<td>The start line of the TSS zone $k$</td>
</tr>
<tr>
<td>$l_{tm,k}$</td>
<td>The termination line of the TSS zone $k$</td>
</tr>
<tr>
<td>$O$</td>
<td>The observation area for planning paths</td>
</tr>
<tr>
<td>$P_c(s_i)$</td>
<td>The penalty cost of course change at node $s_i$</td>
</tr>
<tr>
<td>$P_a(p)$</td>
<td>The penalty function related to time schedule of path $p$</td>
</tr>
<tr>
<td>$P_s(s_i)$</td>
<td>The penalty cost of speed change at node $s_i$</td>
</tr>
<tr>
<td>$r$</td>
<td>The major semi-axis of the elliptical domain developed by Fujii</td>
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<th>Description</th>
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<tr>
<td>( r_{v_i}, \dot{s}_{v_i} )</td>
<td>Current positions of vessel ( v_i )</td>
</tr>
<tr>
<td>( r_{v_j}, \dot{s}_{v_j} )</td>
<td>Current positions of vessel ( v_j )</td>
</tr>
<tr>
<td>( \dot{r}<em>{v_i}, \dot{s}</em>{v_i} )</td>
<td>Speed of vessel ( v_i )</td>
</tr>
<tr>
<td>( \dot{r}<em>{v_j}, \dot{s}</em>{v_j} )</td>
<td>Speed of vessel ( v_j )</td>
</tr>
<tr>
<td>( R )</td>
<td>Range</td>
</tr>
<tr>
<td>( \dot{R} )</td>
<td>Range rate</td>
</tr>
<tr>
<td>( R_{ba} )</td>
<td>The longitudinal radius in the aft domains developed by Arimura</td>
</tr>
<tr>
<td>( R_{bf} )</td>
<td>The longitudinal radius in the fore domains developed by Arimura</td>
</tr>
<tr>
<td>( R_s )</td>
<td>Radius of circular range for selecting encounters</td>
</tr>
<tr>
<td>( R_\theta )</td>
<td>Radial distance from the ship center to the different vertices of the polygon at the polar angle ( \theta )</td>
</tr>
<tr>
<td>( s )</td>
<td>The minor semi-axis of the elliptical domain by Fujii</td>
</tr>
<tr>
<td>( s_i )</td>
<td>The origin point of a navigational path</td>
</tr>
<tr>
<td>( Safety \ (p) )</td>
<td>Safety consideration for path ( p )</td>
</tr>
<tr>
<td>( S_\theta )</td>
<td>The transverse radius in the port and starboard sides of Arimura’s domain</td>
</tr>
<tr>
<td>( sc_{ij} )</td>
<td>Safety cost for segment ( i ) with respect to constraint ( j )</td>
</tr>
<tr>
<td>( s_i )</td>
<td>The waypoints of a navigational path while ( i = 2, \ldots, I )</td>
</tr>
<tr>
<td>( s_{i+1} )</td>
<td>The destination point of a navigational path</td>
</tr>
<tr>
<td>( SD_n (\tau) )</td>
<td>Ship domain around ship ( n ) at time ( \tau )</td>
</tr>
<tr>
<td>( SD_{os} )</td>
<td>The length of the line connecting the centers of a ship pair</td>
</tr>
</tbody>
</table>
inside the OS domain

\( SD_{se} \) \hspace{1cm} Ship domain with one standard error

\( SD_{ts} \) \hspace{1cm} The length of the line connecting the centers of a ship pair inside the TS domain

\( SE \) \hspace{1cm} Standard error

\( \text{Smooth} \ (p) \) \hspace{1cm} Path smoothness for path \( p \)

\( SP(t) \) \hspace{1cm} Solution space at time \( t \)

\( t_0 \) \hspace{1cm} The current clock time

\( T_{90} \) \hspace{1cm} Time to time to 90 degrees heading

\( \text{TCPA}_{\text{lim}-\alpha} \) \hspace{1cm} Limiting value of TCPA

\( T_l \) \hspace{1cm} The lower limit of arrival time schedule

\( t_i \) \hspace{1cm} Travel time of segment \( i \)

\( \text{Time} \ (p) \) \hspace{1cm} Total travel time for path \( p \)

\( T_r \) \hspace{1cm} Time required to initiate a necessary manoeuvre

\( T_u \) \hspace{1cm} The upper limit of arrival time schedule

\( v \) \hspace{1cm} Ship instantaneous speed

\( v_s \) \hspace{1cm} The vessel service speed

\( v_i \) \hspace{1cm} Speed at segment \( i \)

\( v_m \) \hspace{1cm} The minimum steerage speed

\( v_{\max} \) \hspace{1cm} Maximum achievable speed

\( w(E) \) \hspace{1cm} Weight function in relation with \( E \)

\( w_c \) \hspace{1cm} Weight coefficient of comfort consideration
List of Symbols

\[ w_d \] Weight coefficient for travel distance

\[ w_e \] Weight coefficient of economy consideration

\[ w_f \] Weight coefficient for fuel consumption

\[ w_s \] Weight coefficient of safety consideration

\[ w_{sm} \] Weight coefficient for path smoothness

\[ w_t \] Weight coefficient for travel time

\[ w_{ts} \] Weight coefficient for time schedule constraint

\[ x_o, y_o \] Coordinates of OS

\[ x_t, y_t \] Coordinates of TS

\( \alpha \) The set of parameters governing the zero-speed domain

\( \alpha_\theta \) Normalized radial distance of the domain when the vessel is stationary at the polar angle \( \theta \)

\( \beta_1, \beta_2 \) Cost rates of penalty function related to arrival time schedule

\( \delta_{o,x} \) Relative bearing of TS with respect to OS

\( \Delta \) Angular interval discretization step in degree

\( \Delta v_{\min}, \Delta v_{\max} \) The lower and upper limits of comfortable speed change

\( \Delta \theta_{i,i+1} \) Angular course change at node point \( s_i \)

\( \Delta \theta_{i,j} \) Angular difference between the ship heading and the direction of boundary line \( l \)

\( \Delta \theta_{i,\text{sd}} \) Angular difference between the ship heading and the direction of sideline of TSS

\( \Delta \theta_{\min}, \Delta \theta_{\min} \) The lower and upper limits of comfortable course change
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi_i$</td>
<td>Safe distance between ship in segment $i$ with respect to constraint $j$</td>
</tr>
<tr>
<td>$\xi_p$</td>
<td>The safe distance to the channel limit on the port side</td>
</tr>
<tr>
<td>$\xi_s$</td>
<td>The safe distance to the channel limit on the starboard side</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Ship heading of segment $i$</td>
</tr>
<tr>
<td>$\theta_k$</td>
<td>A general direction of traffic flow for TSS zone $k$</td>
</tr>
<tr>
<td>$\theta_l$</td>
<td>Direction of boundary of TSS zone</td>
</tr>
<tr>
<td>$\theta_{sd}$</td>
<td>Direction of side line $l_{sd}$</td>
</tr>
<tr>
<td>$\theta_o$</td>
<td>Heading of OS clockwise from the north direction</td>
</tr>
<tr>
<td>$\theta_{o,T}$</td>
<td>Heading difference between OS and TS</td>
</tr>
<tr>
<td>$\theta_t$</td>
<td>Heading of TS clockwise from the north direction</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Parameter in the speed function</td>
</tr>
<tr>
<td>$\lambda_f, \lambda_a, \lambda_p, \lambda_s$</td>
<td>Parameters in the speed function in the fore, aft, port and starboard sides</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Parameter in the speed function</td>
</tr>
<tr>
<td>$\mu_f, \mu_a, \mu_p, \mu_s$</td>
<td>Parameters in the speed function in the fore, aft, port and starboard sides</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Parameter of the exponential weight function</td>
</tr>
<tr>
<td>$\omega_{cl}$</td>
<td>Coefficient related to the channel limit</td>
</tr>
<tr>
<td>$\kappa(s_i)$</td>
<td>Curvature at node point $s_i$</td>
</tr>
</tbody>
</table>
CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

1.1.1 Ship Domain in Marine Navigation

Navigational safety in the maritime transportation is among the top concerns in the marine sector and this is due to its huge consequences to human, assets and the environment. The concerns for navigational safety have been increasing over time because of the expanding world fleet deployed to meet the demands of waterborne transport (Soares and Teixeira, 2001).

Navigational safety is highly related to human factors. Investigations based on worldwide accident database claimed that human error is the primary cause of collisions. A report from Department of Transport of UK (Bryant 1991) showed about 89-96% of collisions are caused by some form of human errors. A research conducted by Nautical Institute indicated that 60 percent of cases of collisions and grounding are caused by direct human error (Gale and Patraiko, 2007). The research also presented two major human related causes, i.e., insufficient assessment of the situation (24%) and poor look out (23%).

Given this understanding, various navigational aids have been invented to facilitate navigators in safe navigation. For example, to enhance the assessment of navigational situation, Electronic Chart Display and Information System (ECDIS)
have been developed to offer automatic warning of nearby obstacles and ships. ECDIS displays information from the Electronic Navigational Charts (ENC) and integrates position information from the Global Positioning System (GPS) and other navigational sensors, such as Automatic Radar Plotting Aid (ARPA) and Automatic Identification Systems (AIS). ECDIS manufacturers often meet International Maritime Organization (IMO) requirements by allowing users to specify a safety domain, based on which warnings will be triggered when risk of collisions exist.

Fujii and Tanaka (1971) first used the concept of ship domain as a principal criterion of navigational safety. Since then, it has played an important role in marine traffic engineering and navigators have used ship domain to help them to assess risk of collision (Fujii and Tanaka, 1971, Goodwin, 1975, Pietrzykowski, 2008, Pietrzykowski and Urías, 2009), take avoidance actions (Dove et al., 1986, Zhao et al., 1994) and plan navigational paths (Smierzchalski and Michalewicz, 2000, Szlapczynski, 2011). Traffic simulation (Davis et al., 1980, Coldwell, 1983) and optimal path planning (Smierzchalski, 2000, Szlapczynski, 2011) have also employed this concept to fulfill the safety requirement.

Although ship domain has been applied in both open waters and restricted waters, it has been more useful in restricted waters. Because of high traffic density in restricted waters, ships are more likely constrained by channel or fairway limits and have to interact with more ships. The manoeuvring spaces for ships are limited and it is less easy to choose a route freely. In addition, ships have to comply strictly with more traffic rules, including the International Regulations for Preventing Collisions at Sea (COLREGS) and certain port rules. These restrictions may make other safety
Chapter One: Introduction

criteria less applicable; for example, the commonly-used Distance at Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) consider only the location and relative speed of the ships but not factors such as the dimension of ships.

1.1.2 Problems in Ship Domain for Navigation

One significant problem in the application of ship domain is its varied interpretations. The most representative definition of ship domain made by Goodwin (1975) is ‘the surrounding effective waters that the navigator of a ship wants to keep clear of other ships or fixed objects’. This definition implies that ship domain is considered by one of the two meeting ships. However, it is widely recognized that safe navigation water requires actions of both ships (Zhao et al., 1993). Furthermore, in Goodwin’s definition, the domain is considered a subjective concept (Zhu et al., 2001), i.e., this is the space that the navigator ‘wants’ to be keep to be safe. However, this interpretation allows it to be applied in risk assessment but not in path planning which requires a representation of resultant clear area between ships. Pietrzykowski (2008) has concluded that the concept of domain should be understood as an ‘effective’ area around a ship that the navigator maintains to be clear of other objects. The conflicting understanding of ship domain has induced much research.

Moreover, there is no general agreement on the shape of ship domain. A number of researchers, for example, Goodwin (1975) and Davis (1980) have proposed circular domains while Fujii (1971), Coldwell (1983) and Kijima (2003) have adopted elliptical domains and others, for example, Smierzchalski (2000) and Pietrzykowski (2006, 2009) have used polygonal domains. An empirical investigation on the
appropriate shape of the domain would be useful.

Another major difficulty in the study of ship domain is identifying the factors affecting its shape and size. Reviews of literature (Goodwin, 1975, Coldwell, 1983, Zhao et al., 1993, Zhu et al., 2001, Pietrzykowski and Uriasz, 2009) have shown that ship domain is mainly affected by a number of factors, such as

- Size, type and manoeuvrability of Own Ship (OS);
- Relative speed and bearing of the Target Ship (TS);
- Encounter type;
- Water type and traffic density in the navigating area;
- Human factors including knowledge, skills, nationality, mental and physical qualities;
- Hydro-meteorological condition such as weather, tide, current and wind.

Although various methods have been developed to determine the shape and size of ship domain, the factors that should be considered while determining its boundary and how the factors affecting ship domain are still open to question (Pietrzykowski and Uriasz, 2009). In addition, several essential factors, such as human factors and visibility have not been well considered to date.

In addition, most of the previous models either completely lack empirical support in deriving the ship domains (Smierzchalski, 2000, Kijima and Furukawa, 2003, Tam and Bucknall, 2010a) or have little empirical knowledge but misuse them (Fujii, 1971, Coldwell, 1983).
Finally, it is still not clear how the ship domain is applied in path planning. Most previous studies (Goodwin, 1975, Tran et al., 2001, Pietrzykowski and Uriasz, 2006, Pietrzykowski, 2008) applied the ship domain only in risk assessment and collision avoidance for a close encounter involving two ships but none of them have considered its application in planning navigational paths under the interaction of multiple ships and real geometric and geographical constraints.

The gaps in the study of ship domain identified above are the motivations for this research. A rigorous approach to model ship domain that is capable of facilitating risk assessment as well as path planning in restricted waters is the focus of this work.

1.2 OBJECTIVE AND SCOPE

1.2.1 Objective of the Research

The objective of this research is to develop an empirical model of ship domain that can be effectively applied to navigational path planning in restricted waters.

1.2.2 Scope of the Research

The ship domain model proposed in this research is limited to navigation within restricted waters, as this study only utilizes data of ship movements within the Singapore port and Singapore Straits in both day and night conditions.
1.3 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters as structured in Figure 1.1.

Chapter 2 outlines the five-stage methodology of the thesis. Based on a critical review of the ship domain, a new concept of the model is proposed, followed by its mathematical formulation in Chapter 3. The calibration process and results are described in Chapter 4 together with the evaluations of the model. The method of model interpretation and application is then described in Chapters 5 and 6. Chapter 7 summarizes the key findings of this research and highlights the potential areas for future work.
Chapter One: Introduction

Background and motivation
Objective and scope
Organization of the thesis

Chapter Two: Methodology

Model formulation
Model calibration
Model evaluation
Model interpretation
Model application

Chapter Three: Formulation of Ship Domain Model

Critical review of concept
Conceptual model development
Mathematical model formulation

Chapter Four: Calibration and Evaluation of Ship Domain Model

Data collection and preparation
Calibration of ship domain model
Evaluation of ship domain model

Chapter Five: Interpretation of Ship Domain Model

Comparisons of ship domains
Interpretation of ship domain in encounter
Navigators’ perception of ship domain

Chapter Six: Model Application in Path Planning

GA-based path planning
Illustration of ship domain in path planning

Chapter Seven: Conclusions and Recommendations

Conclusions and contributions
Potentials of future research

Figure 1.1 Structure of Thesis
2.1 INTRODUCTION

This chapter presents the methodology of this study on developing and applying ship domain model in restricted waters for navigational safety. Following the general procedure of model development, the study of ship domain consists of five steps, i.e.,

1) Model Formulation
2) Model Calibration
3) Model Evaluation
4) Model Interpretation
5) Model Application

These steps shall be explained sequentially in details in the following sections.

2.2 MODEL FORMULATION

The purpose of model formulation is to derive a mathematical representation of the ship domain. To do that, it necessary to conduct a comprehensive literature review to understand fully the previous works related to the ship domain. A number of issues need to be examined at the onset before a good model for ship domain can be defined. These relate to (a) the shape of the domain and their mathematical representations; (b) the factors affecting the size of the domain and the functional relationships governed by these factors as well as (c) the use of the ship domain, i.e.,
whether a single ship domain with each ship pair or a combination of individual ship domains for each of the pair. The review is also intended to identify the gaps and weaknesses of existing ship domain models so that improvements to these can be proposed.

Following the literature review, a suitable mathematical formulation of the ship domain is proposed. The model adopted is divided into three portions, the representation of domain shape, the representation of the basic domain size for stationary ship and a ship speed function effect. The process of formulation of each of these portions is described in greater details in Chapter 3.

2.3 MODEL CALIBRATION

In this step, the proposed ship domain that was formulated earlier will be calibrated using navigational data. A set of ship movements within the Singapore port over a 4-hour period in the daytime and 3-hour period in the nighttime are used for the calibration process. Since the formulation of the ship domain follow three parts, i.e., the domain shape, the ship domain for stationary ships and a speed function effect, the calibration needs to address all these issues. It is possible to adopt a simultaneous calibration procedure so that the parameters of the model for all three portions can be obtained in a single pass. However, this will result in greater instability due to many degrees of freedom in the calibration process.

The proposed procedure is to prescribe a fixed framework for the first portion, i.e., to represent the shape of the domain by 36 sectors of 10 degrees each around the
ship. This formulation allows the investigation of the shape of the domain without prejudice but with sufficient resolution. The second portion, i.e., the size of the ship domain under stationary condition is defined by a single value for each of the 36 sectors representing the radial dimension of the ship domain. Four ship speed functions are defined and calibrated for the third portion, and these represent the effect of speed on the ship domain in the direction of the four axes of the ship, i.e., the fore and aft sides, the port and starboard sides.

By adopting this approach, the calibration will be done sequentially searching for the best-fitted parameters of the domain size and the speed function. Since a single pass may not result in best-fit model, an iterative process is developed.

In addition, to estimate the parameters in the domain model, close encounters need to be extracted from the database of ship movements. Since the specification of the ship domain is unknown, and it is unlikely that the ship domain is of exact circular shape, the selection of close encounters only based on the distance between ships may not be accurate. Therefore, the close encounters to be used for calibration are re-extracted based on updated ship domain model in an iterative manner.

Based on updated close encounters, the best-fit model can be obtained by defining an optimization problem with the objective to minimize the difference between the model behavior and the data descriptions. Due to the amount of parameters in the domain model and the probable non-differential constraint minimization problem, the Genetic Algorithm (GA) \(^1\) is chosen as the optimization technique. Details of

\(^1\) A general introduction of Genetic Algorithm is given in Appendix A.
using GA are described in Section 4.3.3.

In addition, one aspect of investigation in this research is the day and night time effect. For this the daytime and nighttime models of ship domains are calibrated separately.

2.4 MODEL EVALUATION

In order to determine if the calibrated model is suitable, an evaluation procedure is introduced. This is examined in the form of model fitness and reliability. The former is described in terms of the data utilized in the calibration. As encounters between closer ships are more likely to contribute to the calibration process, the number of data used needs to be examined in the iterative process of calibration. The best-fit model is taken to be one in which a stable number of data points is used in the calibration.

Given the non-homogeneity of data in the data space of the study area, ship encounters may not be observed uniformly for all the 36 sectors. This results in non-uniformity in error distribution among the sub-models, i.e., across different sectors, speed bands and day/night conditions. As this is entirely dependent on the observed data, it cannot be corrected. Thus it is best to simply examine the reliability of the model for each sector, each speed band and day/night condition.

As the evaluation process also makes use of the GA results, the evaluation step is combined with the calibration step in a single GA procedure and this is described in
Section 4.4.

2.5 MODEL INTERPRETATION

Having obtained a suitable model to describe ship domains, the research examines the implication of using this domain in comparison with other measures of navigational safety. Using several case studies, the proposed domain is compared with domains derived from previous studies. This is to examine the superiority of the proposed model over existing models. This involves a systematic comparison of the domain shape and size taking into account other factors, i.e., ship heading and bearing, whether the domain is around OS or TS.

Besides this, the proposed domain is compared with the use of Distance at Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) in a situation of two-ship encounter. This is to examine whether a better understanding of near encounters among ships from the ship domain can facilitate navigators to adopt better collision-avoidance actions.

Another area to be examined is the variations of the perception of domain by navigators. This is done by introducing a stochastic element in the model and investigating its distribution from the derived model.
2.6 MODEL APPLICATION

To further show the usefulness of the model in navigation, two aspects of navigation are investigated. They are (a) the influence of domain on the changes in the optimal paths chosen by ships and (b) the influence of domain on the travel times of ships, subject to the changes in navigational paths. To illustrate these effects, two case studies are formulated and they are based on the port waters of Singapore.

In determining the navigational paths, pilots are assumed to optimize their ship movements based on a combination of factors influencing safety, economy and operational comfort. The problem is formulated as an optimization problem subject to the constraints governed by the appropriate domains around ships as well as geometric constraints of the navigational channels. The optimization problem is solved using GA because: firstly, GA is flexible in dealing with all types of domain (Smierzchalski, 1999, Tam and Bucknall, 2010b, Szlapczynski, 2011); secondly, some decision variable, for instance, the decision variable of ship speed is probably in discrete format. The mathematic model is inherently weak in solving mixed discrete-continuous design optimization because of potential existence of multiple local minima in the search space. The GA-based path planning process is described in Chapter 6.

2.7 SUMMARY

This chapter has presented the whole methodology of developing ship domain model. It includes the concept derivation and model formulation, model calibration
and evaluation, model interpretation and finally the model application. A brief description of deriving the concept and formulating the model of ship domain are firstly given. An iterative method of calibrating the model is strategically proposed. Genetic Algorithm is introduced to solve the optimization problem for model calibration. The model will be interpreted in three aspects. The method of applying the ship domain in the process of GA-based path planning is lastly addressed. The five-step methodology of developing ship domain model will be discussed sequentially from Chapter 3 to Chapter 6.
3.1 INTRODUCTION

Ship domain is important in safe navigation at seas. Pilots and navigators have been accustomed to employing ship domain to assess risk, avoid collisions, and devise a safe path planning. Although ship domain has been adopted for years, there are still a number of issues which are not well understood. Firstly, many experts have given varying definitions of ship domain, based on unique experiences and judgments. Moreover, depending on applications, the interpretations of ship domain can also be different. Secondly, ship domain is a complex concept and influenced by many factors. Ship size and speed are two major factors affecting the ship domain but their interrelationship is still not well established. There are also other factors, such as human and environmental elements, which may require further investigations. Thirdly, there are many features of ship domain which have not been agreed among researchers. These include the shape of domain, whether the domain is static or dynamic, deterministic or stochastic. All these have implication on path planning if different formulations of ship domain should be used.

This chapter aims to provide a historical and critical review of ship domain. Following the review, a conceptual ship domain model is proposed and this is followed by a mathematical formulation of the model.
3.2 REVIEW OF CONCEPT

3.2.1 Collision Risk Measures

Measures of collision risk are reviewed in this section as a backdrop to the concept of ship domain. Previous studies have adopted several numerical collision risk measures such as Range, Range Rate (RR), Distance at Closest Point of Approach (DCPA), Time to Closest Point of Approach (TCPA), and a combination of above.

The Range, \( R \), is the distance between two ships. Clearly this is not a sufficient and accurate measure of collision risk. Another measure is the time required to initiate a necessary manoeuvre (Colley et al., 1984), defined as

\[
T_r = \frac{R}{\dot{R}}
\]  

(3.1)

where \( R \) is the range to target and \( \dot{R} \) is the Range Rate (RR) which is the Doppler or radial velocity in radar target tracking and is defined as the velocity along a line extending from the radar or the target, or the closing relative velocity between two objects. This concept of the time required for measuring risk of collisions is characterized by using the relative velocity of the vessels involved in the encounter and consequently compensating for any speed change. However, this measure assumes that every ship behave in the same way regardless of its unique characteristics.

DCPA and TCPA are two other measures used extensively in collision avoidance systems. DCPA and TCPA defined for a specific encounter of vessel \( v_1 \) and \( v_2 \) are
shown in Figure 3.1.

![Diagram of vessel positions and course at CPA](image)

**Figure 3.1 Definitions of DCPA and TCPA (Debnath, 2009)**

The vessel $v_1$ and $v_2$ are at their current positions $(r_{v_1}, s_{v_1})$ and $(r_{v_2}, s_{v_2})$ at speeds of $(r_{v_1}', s_{v_1}')$ and $(r_{v_2}', s_{v_2}')$ respectively at time. If the two ships maintain their speeds and courses, they will reach at the Closest Point of Approach (CPA) after a time period equal to TCPA and the distance at the CPA between ships is DCPA.

The safety criterion based on DCPA and TCPA is defined by setting the limiting values as

$$TCPA \geq TCPA_{lim}$$ (3.2)

$$DCPA \geq DCPA_{lim}$$ (3.3)

When the limiting values of either DCPA or TCPA are violated, collision warning alarms are often triggered. Different limiting values are usually adopted by different navigators based on their experience and judgment of the situation such as the weather or environmental conditions.
The main reason why DCPA and TCPA are commonly used is that they are unambiguous and independent of other not-so pertinent factors in navigation. There is an abundance of related literature in which equations using DCPA and TCPA are used to measure the risk of collisions (Kearon, 1977, Lisowski, 2001, Debnath and Chin, 2010). Although the calculated measures based on DCPA and TCPA are useful in evaluating collision risk, they still suffer certain limitations. Firstly, they could not take into account the influence of ship size as well as different encounter types. Secondly, the magnitude of these measures only suggests the severity of the situation and is unable to advise navigators on the necessary follow-up actions.

3.2.2 Definition of Ship Domain

Collisions risk is often viewed in terms of space separation, which leads to the use of ship domain. In a previous review of ship domains, (Fujii and Tanaka, 1971, Goodwin, 1975, Coldwell, 1983, Zhao et al., 1993, Zhu et al., 2001, Pietrzykowski & Uriasz, 2009), different definitions have been found and they are listed in Table 3.1.

One critical question which has been debated (Pietrzykowski and Uriasz, 2009) is whether the ship domain describes the intended area the navigator wants to maintain from other vessels or the actual area she keeps from other vessels. Based on this, two concepts of ship domains emerge: desirable ship domain and effective ship domain. The desirable ship domain is the area around a ship which the navigator feels safe when it is without the presence of other ships or objects. This is often used by the own ship to assess the varied risk of nearby target ships or objects and to prioritize these in risk level for potential collision-avoidance action. The effective
domain suggested by Pietrzykowski (2009) supposes an interaction between own ship with other ships or static objects. This is deemed to be more objective better suited for path planning and traffic simulation as they are more reflective of actual situations. Most definitions of ship domain except for Zhu’s subjective domain (2001) in Table 3.1 adopt the concept of effective ship domain as indicated in italics.

### Table 3.1 Definitions of Ship Domain in Existing Literature

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fujii and Tanaka (1971)</td>
<td><em>Effective</em> domain around a vessel under way which most navigators of following vessels would avoid entering. (TS)</td>
</tr>
<tr>
<td>Goodwin (1975)</td>
<td>The <em>effective</em> area around a ship which a navigator <em>would like</em> to keep free with respect to <em>other ships and stationary objects</em>. (OS)</td>
</tr>
<tr>
<td>Coldwell (1983)</td>
<td>The <em>effective</em> area around a vessel which a <em>typical</em> navigator <em>actually</em> keeps free with respect to other vessels. (OS)</td>
</tr>
<tr>
<td>Zhao et al. (1993)</td>
<td>A water area around a vessel which <em>is needed</em> to ensure the safety of navigation and to avoid collision</td>
</tr>
<tr>
<td>Zhu et al. (2001)</td>
<td>The subjective domain is the waters that a navigator really ‘wants’ to be kept safe, usually used of risk assessment by the navigator, while the objective domain is the fact that a navigator ‘has to’ accept.</td>
</tr>
<tr>
<td>Pietrzykowski and Uriasz (2009)</td>
<td>An <em>effective</em> area around a ship that the navigator maintains clear of other objects. Entering the ship’s domain is interpreted as a threat to navigational safety.</td>
</tr>
</tbody>
</table>

Nevertheless, effective domains should also reflect the intended or expected result of navigational behavior. A number of researchers (Fujii and Tanaka, 1971, Goodwin, 1975, Coldwell, 1983) have derived their ship domain empirically using data of shipping movements, taking into account possible interrelated factors affecting the ship domain. Some of these factors include ship dimension, ship type, manoeuvrability, speed, encounter type, and even environment factors as well as human factor. Those will be further discussed in the following section.
3.2.3 Factors Influencing Ship Domain

The size and shape of the ship domain may depend on a number of factors, and these can be divided into several categories:

- Physical factors specific to the ship, for example, geometric dimensions of the ship, the type of ship and other manoeuvrability characteristics;
- Traffic dynamic factors such as the positions, speeds and headings resulting in different ship encounter types;
- Environmental factors general to all ships in an area, for example the tidal and current conditions, visibility and other weather conditions.
- Human factors, for example, navigator’s knowledge, skills, length of sea experience, nationality, mental and physical conditions.

In the following section, the factors affecting the domain shape and size will be examined in further details.

3.2.3.1 Physical factors

1) Dimension of ship

The dimension of ships is often represented by ship Length Overall (LOA) and beam. Depending on the ship type, since the beam of the ship is often considered to be a function of LOA, it is often sufficient to represent the ship dimension in terms of LOA alone.

A number of researchers (Goodwin, 1975, Coldwell, 1983, Zhu et al., 2001, Pietrzykowski and Uriasz, 2006, Kao et al., 2007) have considered the size of ship
domain to be proportional to the LOA while others (Fujii and Tanaka, 1971, Smierzchalski, 2000, Tran et al., 2001, Kijima and Furukawa, 2003b) have considered a linear relationship between domain size and LOA.

Fujii (1971) was first to propose a relationship between the ship size and domain, based on overtaking encounters in Japanese waters. The size of the elliptical domain is governed by the major and minor semi-axis ($r$ and $s$, respectively) are these are assumed to be proportional to the ship length as

$$r = 7L \pm L$$  
$$s = 3L \pm 0.5L$$

where $L$ is the ship length. Goodwin (1975) proposed the domain governed by three sectors defined by varying ratios of the length of ship. Arimura (1994) defined a blocking area as a similar concept to ship domain using $R_{bf}$ and $R_{ba}$ to indicate respectively the longitudinal radius in the fore and aft domains and $s_b$ to be the transverse radius in the port and starboard sides. The values of these parameters were further defined by Kijima et al. (2006) as

$$R_{bf} = L + T_{90} \cdot \frac{v}{2}$$  
$$R_{ba} = L + T_{90} \cdot \frac{v}{4}$$  
$$S_b = B + D_T$$

where $B$ and $v$ are ship breadth and speed respectively, $T_{90}$ is the time to 90 degrees
heading and $D_T$ is the tactical diameter of a ship. Kijima proposed that the blocking area is not only dependent on the length of ship, but also the breadth, although the latter is often decided by a fixed length-breath ratio. This means that it may be sufficient to use LOA as the only physical parameter in defining ship domain.

2) **Type of ship**

The behavior of one vessel behavior may differ a great deal from another. Goodwin (1975) has identified that the ship type is a factor affecting the size of ship domain. Coldwell (1983) also commented if the own ship and the approaching ship are general cargo vessels, the ship domain is likely to be relatively small but if both are either passenger ships or ships carrying dangerous cargo, the domain is expected to be larger. In studying fishing and merchant ships, Coldwell (1983) confirmed that the domain for a fishing vessel is significantly different from that of a merchant vessel.

Although it is useful to consider the ship type in modeling ship domain, ship type is often interrelated to the ship length and the ship manoeuvrability. This may be one reason why ship type is seldom specifically modeled in previous models of ship domain. Another possible reason may be because in many of the studies, ship type information may not be captured in the database.

3) **Manoeuvrability of ship**

The manoeuvrability of the ship is another factor affecting the ship domain. Maneuvering performance of a vessel is often evaluated in terms of turning ability, course changing and yaw checking ability, initial turning ability and stopping ability.
Turning ability is the measure of the ship’s ability to turn the vessel using hard-over rudder (or other primary mean of directional control). This may influence safe spacing and hence the ship domain.

![Variables Describing Ship Manoeuvrability (ABS, 2006)](image)

**Figure 3.2** Variables Describing Ship Manoeuvrability (ABS, 2006)

In developing the blocking area, Kijima and Furukawa (2003, 2006) proposed several terms to describe maneuverability, such as the advance, the tactical diameter and the time to 90 degree. As shown in Figure 3.2, these variables are used to evaluate the ship’s ability to turn (ABS, 2006).

To represent ship manoeuvrability, Arimura (1994) proposed a relationship of ship’s length and speed, which is consistent with IMO standard on ship’s turning test using parameters of advance and tactical diameters (ABS, 2006). This relationship with respect to the manoeuvrability is also addressed by Zhu et al. (2001) using neural
network. The parameters considered include the ratio of length to breadth, the ratio of breadth to draft (mean), and the block coefficient. However, it was found that the model is highly dependent on the learning samples and it is difficult to generalize this.

Therefore, among the physical factors, LOA is the most important and inherent element affecting the ship domain.

3.2.3.2 Traffic dynamic factor

1) Ship speed

As a dynamic factor, the ship speed refers to the instantaneous speed instead of the service or maximum speed. Zhao et al. (1993) first suggested that the size of a ship domain is influenced by the relative speed of the two encountering ships; and the higher the relative speed, the larger will the ship domain. Tran et al. (2001) has proposed a linear relationship between the relative speed and ship domain. In a different configuration, the safety area developed by Tam and Bucknall (2010a) is also considered a linear function of the speed of target ship. On the other hand, based on a regression model, Smierzchalski (2000) has suggested a non-linear relationship between speed and domain size which is also proposed by Kijima et al. (2006) in their analytical model.

2) Encounter Type

Encounter types are generally defined in accordance with the regulations of COLREGs, even though COLREGs do not distinguish their differences.
Consequently, most marine navigational studies define their own encounter types, often based on their experience and specific purpose (Tam and Bucknall, 2010a, Perera et al., 2011, Wang and Chin, 2012).

![Figure 3.3 Definitions of Encounter Type in COLREGs](image)

In IMO regulations, i.e., COLREGs, an approaching encounter is divided into three types i.e., overtaking (or being overtaken), head-on and crossing. The distinctions are illustrated in the Figure 3.3.

- **Head-on**

  Head-on encounter is defined when two ships are approaching each other on a reciprocal or near-reciprocal course. By night this is viewed when one ship can see the masthead lights of the other in a line or nearly in a line and/or both sidelights. In such situations, both ships are expected to alter their courses to starboard side and allow passing on the port side.
• **Overtaking or being overtaken**

A ship is deemed to be overtaking when she is coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is overtaking, and that at night, she is able to see only the sternlight of that vessel but not her sidelights. Generally speaking, the overtaking ship should give way to the overtaken ship by altering course to starboard, if she is on the starboard quarter of the overtaken ship or to the port side if she is on the port quarter of the overtaken ship.

• **Crossing**

When two vessels are crossing each other so as to involve the risk of collision, the ship which has the other on her starboard side is the give-way ship, which is to keep out of the way of the other and if possible, avoid crossing ahead of the other. The give-way ship is expected to take early and substantial action to keep herself well clear of the other while the stand-on ship is to keep her course and speed. Any avoidance action taken by stand-on ship is not to alter the course to port side for a vessel on her own port side.

The encounter types described in COLREGs have been widely applied and observed in navigation. However, it may not be so easy to explicitly state these encounters in a numerical fashion that is suitable for modeling.

In existing literature, the general accepted practice is to classify ship encounter types by the relative bearing and heading difference (Yu-Hong and Chao-Jian, 2005, Tam and Bucknall, 2010a, Perera et al., 2011, Wang and Chin, 2012). Consequently, to
take into account different encounter types in modeling ship domain, the size and shape of the ship domain is assumed to be dependent on the bearing of approaching ship and the difference in the headings between the two ships.

One exemplary method of representing this is given by Wang and Chin (2012) as shown in Table 3.2 and Figure 3.4.

**Table 3.2 Traffic Encounter Classification by Wang and Chin (2012)**

<table>
<thead>
<tr>
<th>Relative Bearing (degree)</th>
<th>Heading Difference (degree)</th>
<th>&lt;-180, -112.5&gt;</th>
<th>&lt;-112.5, -67.5&gt;</th>
<th>&lt;-67.5, -10&gt;</th>
<th>&lt;-10, 10&gt;</th>
<th>&lt;10, 67.5&gt;</th>
<th>&lt;67.5, 112.5&gt;</th>
<th>&lt;112.5, 180&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td>&lt;-180, -170&gt;</td>
<td>SP</td>
<td>SP</td>
<td>HO</td>
<td>HO</td>
<td>HO</td>
<td>SP</td>
<td>SP</td>
</tr>
<tr>
<td>SP</td>
<td>&lt;-170, -67.5&gt;</td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
<td>SO</td>
<td>SO</td>
<td>SO</td>
<td>SP</td>
</tr>
<tr>
<td>OT</td>
<td>&lt;-67.5, 67.5&gt;</td>
<td>OT</td>
<td>OT</td>
<td>OT</td>
<td>OT</td>
<td>OT</td>
<td>OT</td>
<td>OT</td>
</tr>
<tr>
<td>SP</td>
<td>&lt;67.5, 170&gt;</td>
<td>SP</td>
<td>GW</td>
<td>GW</td>
<td>GW</td>
<td>SP</td>
<td>SP</td>
<td>SP</td>
</tr>
<tr>
<td>SP</td>
<td>&lt;170, 180&gt;</td>
<td>SP</td>
<td>SP</td>
<td>HO</td>
<td>HO</td>
<td>HO</td>
<td>SP</td>
<td>SP</td>
</tr>
</tbody>
</table>

Note: SP: Safe Passing; HO: Head-On; SO: Stand-On; OT: Overtaking/Overtaken; GW: Give-Way.

The values of relative heading of an overtaking encounter are determined based on the definitions stipulated in COLREGs, i.e., coming up with another vessel from a direction more than 22.5 degrees abaft her beam. However, since there is no specific value of the head-on encounter in COLREGs, different values ranging from 10° to 44.5° have been used (Tam and Bucknall, 2010a, Perera et al., 2011, Wang and Chin, 2012). It should be noted that Tam and Bucknall (2010a) have argued that the enlarged range of head-on encounter will provide an additional buffer against the uncertainties when deciding upon the type of encounter between head-on and crossing encounters.
Although the encounter type is well defined using numerical values, it is still a discrete state so that a drastic jump from one encounter type to another is intended. However, the sudden change in navigational behavior due to a different classification of an encounter is not realistic. To account for a more continuous behavior, it may be better to model encounters in terms of bearing and relative headings rather than by encounter classification.

The influences of traffic encounter on ship domain are reviewed as follows. A number of researchers have considered the ship domain to be significantly governed by the relative bearing of approaching ship. Goodwin’s ship domain (1975) consists
of three circular sectors with different radii. In adopting a similar approach, Davis et al. (1980) has argued that when a target ship comes from the starboard side, the own ship becomes a give-way ship and is responsible to take avoidance action; but when the target ship appears on the port side, she is a stand-on ship approaching from port side and no action is required. Hence, in accordance to the responsibility of avoidance actions outlined in COLREGs, ships are generally more sensitive to target ships approaching from starboard side and thus the starboard sector of the domain is larger than the port sector. Furthermore, as COLREGs recommend ships to pass port to port rather than starboard to starboard, navigators will be under heavy pressure to comply and therefore have the tendency to provide more passing distance if they ever pass starboard to starboard. The ship domain was derived based on an understanding of the psychological influence on navigation by the COLREGs rather than empirical evidence.

Although Goodwin’s domain is effective in reflecting the influence of encounter types, it is limited because the abrupt changes in the radii between encounters. Davis et al. (1980) modified the Goodwin’s discrete ship domain boundary with an eccentric circle in such a way that the weighting of different areas and the influence of relative bearing are still maintained. Others (Coldwell, 1983, Kijima and Furukawa, 2003, Tam and Bucknall, 2010a, Wang and Chin, 2012) have proposed variations of the basic domain model but all of them have little empirical support.

In summary, the size and shape of ship domain are highly related to encounter types and more specifically the relative bearing and heading difference between ships. It is therefore possible to study ship domains not in fixed categories of ship encounters
but in generalized combinations of bearing and relative headings.

3.2.3.3 Environmental factors

1) Water type

In general, the waters at sea can be divided into three main categories: 1) open sea waterways, 2) restricted waterways and 3) narrow fairway and channel. The traffic densities in the three categories are significantly different. Empirically Goodwin (1975) has found that the size of ship domain to be affected by different operating environment and ship density. As expected, because of more degrees of freedom, the ship domain for the open ocean is greater than that in strait waters which is as shown in Table 3.3. Similarly, the ship domain in congested strait water is smaller than that in a strait with less traffic as shown in Table 3.4.

<table>
<thead>
<tr>
<th>Sea area</th>
<th>Starboard sector (n.m.)^2</th>
<th>Port sector (n.m.)</th>
<th>Stern sector (n.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dover Strait</td>
<td>0.8</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Ocean</td>
<td>2.4</td>
<td>2.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Index of traffic density</th>
<th>Starboard sector (n.m.)</th>
<th>Port sector (n.m.)</th>
<th>Stern sector (n.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.9</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>11.3</td>
<td>0.7</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>7.5</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The effect of water types on the ship domain have been further investigated by Pietrzykowski and his associates (Pietrzykowski, 2008, Pietrzykowski and Uriasz, 2008).

^2 n.m. denotes nautical mile which is 1.852 meters.
2009). In open waters, the factors are: distance to the other ship, relative bearing on the other ship and the other ship’s course. In comparison, the factors in narrow fairways include the distance to fairway axis, deviation from the preset course defined by the fairway axis and rate of turn. Quite clearly, the ship domain in open waters and narrow fairways should be treated differently.

2) Visibility

Visibility may also influence the size of the ship domain. Fujii (1971) pointed out that decreasing visibility will increase the range of an effective domain. However, ironically, he also suggested that further deterioration in visibility does not appreciably influence its size because empirically navigational capacity does not seem to be affected. In a simulator-based experiment under fog conditions with visibility of 0.25 n.m., Goodwin (1975) further confirmed that the ship domain is highly affected by visibility. In a more recent experiment involving no navigational aids, Zhu et al. (2001) found that the magnitude of domain radius is related to the visibility, measured in terms of the distance at which an object or light can be clearly discerned in Figure 3.5. However, it is uncertain if this phenomenon is valid when the pilots are assisted by navigational aids, for example, Automatic Radar Plotting Aid (ARPA) and Automatic Identification Systems (AIS).
3) Other environmental factors

Except for the influence of visibility, other environmental factors, such as wind, tidal current and wave, etc., have not been well considered in the studies of ship domain.

Tanaka (1971) presented the influence of tidal current on the size of effective domain using the major and minor semi-axis \( r \) and \( s \) as

\[
\begin{align*}
    r &= 7L + 5L_0 \frac{u}{Lu_0} \pm L \\
    s &= 3L \pm L
\end{align*}
\]

(3.9)

(3.10)

where \( u \) is the speed of the tidal current in knots and \( L_0 \) and \( u_0 \) are 40 m and 10 knots respectively; the sign of \( u \) is positive for a fair current and negative for a counter current. It may be argued that the empirical equation is very crude since the influence of current on the ship domain is only along the direction of ship speed.
In developing a guarding ring, which is a similar measure of ship domain, Kao et al. (2007) considered the influence of sea state on ship domain. In his study, the sea state was simplified to three linguistic states, i.e., gentle, medium and rough and these are numerically specified based on expert judgment. Although the sea state was claimed to be accounted in the model, the resulting model appears rather crude and highly dependent on subjective expert judgment.

Thus far, environmental factors influencing ship domain have not been adequately studied and this may be due to the difficulty of obtaining objective empirical evidence to verify the relationship. These effects will not be explicitly considered in this research.

3.2.3.4 Human factors

The size and shape of the ship domain have been reasoned frequently on the dependency of human (psychological) factors (Goodwin, 1975, Zhao et al., 1993, Pietrzykowski, 2008). Such human factors include the pilot’s knowledge and skills, his navigational experience and preference, and his physical and psychological condition such as fatigue, stress and health.

In practice, the navigator/pilot determine the shape and size of the ship domain based on a number of factors such as ship speed and length, sea area, but all these are also influenced by his own judgement and perception. While such judgement and perception may be influenced by many of the pilot’s characteristics including his capability, experience and age, it is generally difficult to incorporate such variables in a comprehensive study.
Such variation of navigational behavior has been identified in a number of studies. By investigating human cognitive demands for collision avoidance, Robert et al. (2003) showed that mariner's preference of collision avoidance maneuvers varies quite significantly. In real life tasks, piloting crews frequently make course changes up to 30 degrees to minimize uncertainty. On the other hand, navigators are often reluctant to make large course or speed changes because it is difficult to return to the original course and dynamic state. Kemp (2009) also suggested that a considerable proportion of experienced mariners appear willing to take actions which are in accordance with natural action and opposed to action prescribed by the COLREGs. Therefore, the variability in navigational behavior should not be ignored in navigational behavior studies. The ship domain, as a means of reflecting navigational behavior, should also consider this factor.

However, the component of human factor has been seldom considered in the existing studies on the effective ship domain. It is partially because in most statistical studies, difficulties exist in separating the factors from other crucial factors, such as ship length and speed. Therefore, the influence of behavioral difference was often ignored by averaging out the domain value. In addition, the application of ship domain to traffic studies, for example, path planning and collision avoidance, are only theoretical basis assuming no perception error or variation among navigators exist.
3.2.4 Features of Effective Ship Domain

3.2.4.1 OS domain or TS domain

Another key difference in the different concepts of ship domain is whether to define the domain around OS or TS. Some, for example, Fujii and Tanaka (1971) have defined the domain around the TS (for example, the overtaken ships) while others, for example, Goodwin (1975), Coldwell (1983) have considered domains around OS since it appears to be within the control of the navigator. Details of their domains can be found in Table 3.1. Given these two perspective, it is relevant to consider which is more appropriate.

In investigating this problem, Zhu et al. (2001) considered dividing the encounter/manoeuvre into several stages, assuming that different domain perspectives dominate. They assumed that during stages of assessing collision risk and determining the time to manoeuvre, navigators would consider the domain around their own ship; but when during subsequent stages of altering back to the normal course, navigators would consider the domain around the target ships. This may not be realistic because potentially at any stage the risk of collision may still exist and indeed it is for the purpose of risk assessment that ship domains are to be employed in the analysis. When risk is no longer relevant, the concept of ship domain as a space for safety may also be in application.

In order to find out whether the OS domain or TS domain is better, the advantages and disadvantages are analyzed.
By using the domain around the OS, navigators could evaluate the risk of any target ship based on its relative bearing with respect to the OS. Any TS encroaching the ship domain around the OS will be regarded as posing a risk to the OS. There are several limitations in using such a domain perspective. The most serious limitation is the inability to consider the attributes and kinematic features of the TS. In early studies (Davis et al., 1980, Coldwell, 1983), some ship domain models only focus on OS by treating each TS similar to the OS. Since the ship domain is an effective area between ships, they should encompass the influences of both ships. In more recent works (Smierzchalski, 2000, Kijima and Furukawa, 2003, Pietrzykowski and Uriasz, 2009), domains around OS have also incorporated the influence of target ships. Nevertheless, these models of domain consider only limited features of target ships, such as relative speed (Smierzchalski, 2000, Kijima and Furukawa, 2003) and the size of TS (Pietrzykowski and Uriasz, 2009). In addition, it has been argued that these models lack a theoretical basis (Smierzchalski, 2000) and empirical calibration (Kijima and Furukawa, 2003) and have limited application (Pietrzykowski and Uriasz, 2009).

Moreover, the ship domain around OS may not consider fully the responsibility of avoidance action in an encounter. Goodwin’s domain (1975) considered different weights according to the different sides of the ship. Based on this setting, the OS is more sensitive to ships appearing from the direction of its OS domain with the largest sector. Thus if the largest sector is on its starboard side, the pilot is likely to give way to ships approaching from the starboard side which seems to be compliant with COLREGs. However, this perspective does not differentiate the responsibility of taking avoidance actions between the OS and TS. Therefore, while the ship
domain around OS is applicable in accordance to COLREGs, it does not work well when the OS is a stand-on ship, so that a stand-on OS will still initiate avoidance action before a give-way TS.

In more recent works on collision risk assessment (Tam and Bucknall, 2010a) and path planning (Tam and Bucknall, 2010b, Wang and Chin, 2012), domains around TS have been proposed. In general, it is more straightforward to apply this perspective in path planning. Unlike models with domain around OS without taking into account the characteristics of TS, the domain around TS offers a perspective to differentiate the risk of target ships based their attributes and kinematic information. Hence, for larger target ships and with higher speeds, bigger domains around them can be formulated. Regarding the responsibility of taking avoidance action, the domain of stand-on TS were even neglected (Tam and Bucknall, 2010a), based on the assumption that the ‘give-way’ ship is responsible to take action first. Consequently, the different dimensions of domains around target ships could represent the risk level of different target ships to an individual OS.

Furthermore, this perspective overcome the criticism of Zhao et al. (1993) in a particular situation when a give-way ship passing a stand-on ship aft will keep an extra space on the back of target ship. Since the starboard side of the give-way ship is larger than the aft side of stand-on ship, the former ship still needs to take action to displace herself outside the her starboard sector of domain. As a result, the observed aft side of stand-on ship is larger than it was estimated in Goodwin’s domain (1975). However, if the domain of the TS is used in this situation, the existing contradiction will be resolved.
Though the perspective of the domain around TS seems to be able to mitigate the limitations of the first perspective, it is still unavoidably limited in treating every OS equally. For instance, a large ship and a small ship are allowed to reach the same limiting boundary of domain of a third ship which is the TS of the first two ships. It may not be so critical to the third ship as an OS since she will react to the other two ships differently. The mutual and yet unequal consideration between OS and TS remains a problem to be resolved in ship domain studies.

Tam and Bucknall (2010a) developed a safe area around TS with dimension and shape dependent on the type of encounter as well as the relative speed of the OS and the obstacle concern. Although their domains around TS could distinguish the responsibility of taking avoidance actions, the parameters in their ship domain have not been calibrated empirically. Wang and Chin (2012) modeled the domain of TS by adding the influence of encounter types to the blocking area suggested by Kijima and Furukawa (2003). The model is capable of considering the reasonability of taking avoidance actions under different encounters outlined in COLREGs. However, the model is also limited in calibrating the adopted parameters.

Therefore theoretically, whichever perspective adopted, only one of the players involved in an encounter is comprehensively considered in generating the ship domain. This will result in defining the ship domain clearly and consistently between two ships. Without considering the characteristics of both OS and TS, it is always problematic to describe the ship domain in whichever perspective. Hence there is need to develop more advanced model of ship domain to comprehensively consider the influence of encountering ships.
3.2.4.2 Shape of ship domain

The existing ship domains, regardless of the factors considered and the ways of being interpreted, can be categorized into different types based on the geometrical shape. Three major categories depending on the edge of the boundary have been identified, i.e., circular domain, elliptical domain and polygonal domain. For each category, variations from the standard shape exist.

1) Circular domain

The criterion of safe passing distance generally forms up a standard circular domain, as adopted in ARPA. A collision-avoidance action should be undertaken when the DCPA is less than a limiting value, which is also named as the desired passing distance or safe passing distance. This concept results in a circular area around a ship, of which any encroachment is prohibited for safety. Many studies of collision avoidance (Kwik, 1989, Tran et al., 2001) and path planning (Zeng, 2003, Tsou et al., 2010) have widely adopted some forms of safety area in the circular shape.

One of the key advantages of standard circular domain is its simplicity in definition, i.e., only the radius of circle is needed. This characteristic makes it possible to apply straightforward mathematical methods in calculating the collision-avoidance actions and paths in navigation (Kwik, 1989, Lisowski and Smierzchalski, 1995, Tran et al., 2001). However, the domain is too simplistic to be realistic as a variety of factors affecting navigational behaviors are neglected.

Considering that the domain is unlikely to be equal all round, Goodwin (1975) proposed a circular-type ship domain whose edges are described as three circular
arcs as shown in the Figure 3.6 (a). The three sectors represent the starboard, port and astern sides based on the relative bearing of target ships or objects. However, one of the major limitations of Goodwin’s model is the discontinuity of domain edge, which results in sudden action changes in response at the transition between sectors. Besides, the critical values of the relative bearings used for dividing different sectors have yet been justified.

Figure 3.6 Circular Domains of Different Radii

To overcome the problem of discontinuity, Davis et al. (1980) considered a circular domain edge but adjusted the position of the OS as a phantom ship away from the centre of the domain in Figure 3.6 (b). Although this model retains the concept of different weights in the different directions, the difficulty lies in finding the locus of
the phantom ship to make the domain model complete in representation.

Also based on Goodwin’s domain, Zhao et al. (1993) proposed a fuzzy boundary of ship domain using fuzzy set theory. As shown in Figure 3.6 (c), the shape of the domain is still composed of circular arcs; while the radius of the sector is no more deterministic and this is done by adding a fuzzy component. Although the concept of fuzzy boundary domain extends the term of ship domain, it still suffers the same limitation as the Goodwin’s domain in the discontinuity of domain boundary.

2) Elliptical domain

As shown in Figure 3.7 (a), the first ship domain proposed by Fujii (1971) was a standard elliptical one for an overtaking encounter. Derived from a large recorded database, the domain forms a symmetrical ellipse defined by the semi-major axis and semi-minor axis. The domain is argued to be applicable for both open waters and restricted waters but limited to overtaking encounters. Coldwell (1983) further extended this meeting (head-on) in Figure 3.7 (b) and overtaking encounters in Figure 3.7 (c) but with dissimilar semi-major axis and semi-minor axis. By assuming only head-on encounters, they considered only a half ellipse on the fore side without defining the lower half or the ellipse for the aft side.

Considering an elliptical-type domains and calling it a “blocking area” or “watching area”, Kijima (2003) proposed two half ellipses with same semi-minor axes but different semi-major axes on the fore and aft direction in Figure 3.7 (d). Extending from the unequal semi-ellipses but symmetrical about the major axis, Wang and Chin (2012) considered an asymmetrical elliptical domain with unequal longitudinal
axis and lateral axis in Figure 3.7 (e). This representation is able to mimic the pilot’s responsibility in taking action, especially in the crossing encounter and head-on encounter according to the specifications in the COLREGs.

Figure 3.7 Domains of Elliptical Shape

The major advantage of adopting elliptical-type ship domain over circular domain is the ability to account for the influence due to different encounter types in accordance with COLREGs. However, most of the domains of elliptical shape lack good calibration based on reliable statistical methods. It remains difficult to
determine the exact shape of the domain based on empirical evidences.

3) Polygonal domain

The key contribution of the polygon domain over elliptical domain lies in the relaxation of the requirement for a functional shape of the domain. Basically, the boundary of either circular domain or elliptical domain follows a specific mathematical function, which restricts the shape of the domain. Smierzchalski (2000) developed a hexagonal ship domain for a target ship on the basis of ship dimension and speed, and relative dynamic parameters in Figure 3.8 (a). The domain was formulated analytically and justified by kinematical and dynamical properties of objects, navigational regulations and the principles of good sea practice. Although the analytical model makes it possible to define a ship domain clearly, the model still lacks empirical support. Pietrzykowski (2009) adopted a polygonal ship domain for open sea waters using expert research and questionnaires as shown in Figure 3.8 (b). The shape of the model depends on the discrete steps of the ship course, for example, in 45 degree intervals resulting in a ship domain shaped as an asymmetrical octagon. However, due to the manner it is derived, Pietrzykowski does not consider his result to reflect the effective domain. It is also unable to take into account the dynamic properties of the encountering ships compared to the earlier simpler version (Smierzchalski, 2000).

The polygonal domain is fundamentally promising because it is not constrained by any specific shape function. Therefore, by offering a higher degree of freedom, it has the capability of reflecting more correctly the shape of the ship domain bearing in mind the complexities of interaction between ships under different encounter
types.

![Diagram](image.png)

(a) (Smierzchalski, 2000)  
(b) (Pietrzykowski, 2008)

**Figure 3.8 Domains of Polygonal Shape**

### 3.2.4.3 Static and dynamic domain

In general, an object is termed as dynamic if it is able to change with the passage of time. In considering a dynamic domain, it assumes that the shape and size of the domain in whichever perspective will change in the course of the passage of a ship. Such changes may be due to a host of factors which are in themselves dynamic in nature, for example the moods of the pilot or the environmental conditions. In this thesis, the dynamic aspects of the domain are assumed to be due to the changes in ship position, speed and bearing.

1) **Static domain**

The static domain refers to the domain which is invariable of both the ship speed and heading. Most of the domains in the early studies are static ones (Fujii and Tanaka, 1971, Goodwin, 1975, Davis et al., 1980, Coldwell, 1983) because the
purpose of their studies is primarily to develop a domain based on ship and encounter type. Although Fujii (1971) considered their domain in terms of traffic speed and density, their domain remains a static one because the speed and density are considered at a macro level. Some other static domains only focused on the size of ship regardless of the dynamic features (Davis et al., 1980, Coldwell, 1983).

2) Dynamic domain

Dynamic domains become relevant only when ships undergo a navigational process with changing positions, speeds and bearing. Tran et al. (2001) considered a threat zone which accounts for dynamic changes in relative speeds between vessels. The size of the threat zone is dynamically adjusted throughout the navigational process. By taking into account different ship speeds in a navigational process and the rotating domain due to changing bearing, other researchers (Smierzchalski, 2000, Kijima and Furukawa, 2003) have also applied dynamic domains in their studies. Pietrzykowski and Uriasz (2009) have also illustrated how their domains change with respect to the change of heading of TS.

However, there are some criticisms on the use of dynamic ship domains. Pietrzykowski and Uriasz (2009) and Wang et al. (2009) argued the changing shape and size of the domain main hinder the proper assessment of the real navigational situation as the domain may fluctuate wildly from one point in time to another. The argument is also valid in collision avoidance and navigational path planning. Nevertheless the inability of a domain to reflect continuously the navigational decision making process is really not due to the dynamic aspects *per se* but more likely due to the inappropriate shape and size of the domain used.
3.2.4.4 Deterministic and fuzzy domain

In the earlier models, ship domains, are assumed deterministic. It was Zhao et al. (1993) who introduced the idea of a fuzzy boundary of ship domain. This is used in collision avoidance so that only when the relative motion line of a target ship falls just inside the fuzzy boundary depending on a predetermined membership fuzzy function, an avoidance action is needed. Pietrzykowski and Uriasz (2004) extended the concept of fuzzy boundary of ship domain by introducing a ship fuzzy domain defined as a fuzzy area around the ship which the navigator should keep clear of other vessels and objects. They assumed the shape and size of the domain to depend on the assumed level of navigational safety which can be different for different navigators. The fuzzy domain has been applied in both narrow fairways (Pietrzykowski, 2008) and open waters (Pietrzykowski and Uriasz, 2009). The developed fuzzy domain seems to be powerful in representing the navigators’ knowledge in determining the navigational level of safety. The feature makes the model applicable in assessing the risk of collisions.

However, Pietrzykowski (2008) accepted that his domain is not an effective domain around ship. In addition, Pietrzykowski’s fuzzy domain lacks empirical basis since the scenarios used in deriving the domain were hypothetical ones conducted under a desktop environment. Therefore, it is incapable of measuring the true uncertainties in the real situation.

In summary, the gaps and weakness in the existing domain models have been uncovered, i.e., the ill-defined domain shape, the discrete features in the encounter type, the limitations in adopting either domain around OS or TS and the
inappropriateness in dynamic domain, etc. These limitations together with understandings of ship domain from the critical reviews will be addressed in building the conceptual model of ship domain in the following section.

3.3 CONCEPTUAL MODEL DEVELOPMENT

Based on the foregoing critical reviews of ship domain, a conceptual model of the ship domain will be derived in this section.

In this research, it is supposed that the ship domain is an interactive domain between the two ships in a close encounter. Two individual domains around the OS and TS in an encounter are assumed. The proposed perspective should effectively represent the safe navigational water between approaching ships, and reflect the navigational features of both ships and their interactive navigational behavior.

Instead of adopting the simplified and restricted elliptical domain, this study assumes an asymmetrical polygonal shape with small discretized intervals. A dynamic domain is assumed so that while the basic shape of the domain is consistent, of which the size will be enlarged with increasing ship speed.

Furthermore, the required safe distance between ships governed by the edge of the ship domain will also change with the changing relative bearing and heading throughout the encounter. Moreover, variations in the domain size are allowed to account for the different perception of navigators. This is accomplished by considering a normalized stochastic element to be applied consistently regardless of
the different discretized sectors. Due to the stochastic element, instead of the edge, the domain is more likely to be a band.

In so doing, the proposed domain should consider the pertinent factors such as ship length and speed and the stochastic element should address the other less quantifiable factors such as water type, visibility as well as the human factors.

3.4 MODEL FORMULATION OF SHIP DOMAIN

3.4.1 Approaches of Formulating Ship Domain

Previous studies have adopted approaches of three types: analytical, statistical and artificial intelligence approaches. Each of these approaches has unique advantages and limitations and these will be described in the following sections.

1) Analytical approach

Analytical approaches are fundamentally based on a theoretical understanding of the functional relationships between variables. In the case of maritime studies, a firm theoretical basis may not be always found. Often analytical approaches are formed purely based on expert judgment or established rules which may not be empirically justified. In the case of domain studies, analytical studies are mostly dependent on traditionally accepted rules and good practices in navigation. For example, Wawruch (1998) has considered domains purely based on assumed relationship with ship length and width. The approach may be modified, for example, Smierzchalski’s domain (2000) for target ships using DCPA and TCPA concepts, regulations in
force and the principles of good sea practice. However such models are necessarily simple and difficult to be verified empirically. One of the major limitations of analytical approach is its inability to take into account the influence of human factors which has become an important consideration in most domain studies.

The advantage of analytical approaches is its simplicity in application but given the complexities in navigation, analytical formulation is extremely unlikely to adequately model ship domain adequately.

2) Statistical approach

The statistical approach requires a sufficient amount of traffic data of ship encounters, usually based on trajectory information. Fujii (1971) and Coldwell (1983) assumed the boundary of the domain at the position where the local maximum of the traffic density of trajectories is located. On the other hand, Goodwin (1975) assumed that the domain is defined at the position where the number of tracked ships starts overriding the expected number when there is no domain. Under the situation with no ship domain, the traffic around a ship is assumed to be uniformly distributed throughout. The adopted concept implies that it is the presence of the target ship that contributes to the depletion of other ships within the domain area, and therefore is an enhancement of the number of ships outside the domain area. Commenting on these two concepts, Zhao et al. (1993) suggested that Fujii and Coldwell’s concept is suitable for the study of traffic capacity and navigation safety in a channel; while the Goodwin’s concept is suitable for the study of the traffic risks. In fact, both suffer the common limitation of treating all surrounding ships equally regardless of the ship characteristics. However,
it is generally accepted that a bigger ship and with higher speed will require larger ship domain and therefore assuming a uniform density, which amounts to equal domain size for all ships, may not be sufficient to account for such effects.

The statistical approach used to derive the domain is also criticized for failure to separate the factors affecting the domain shape and size. This is an intrinsic limitation of the statistical approach since it is generally difficult to distinguish and even justify the contributions of various factors in a single analysis. Furthermore, most statistical approaches require sufficient amount of data to attain a level of confidence. This may not be a serious obstacle especially in restricted waters as marine traffic have been effectively tracked and recorded.

The key advantage of statistical approaches in establishing domain models is that there are powerful tests to identify contributing factors and to account for uncertainties either due to errors in data recording or simply noise in the model. Nevertheless, statistical approaches require specific assumptions associated with data and functional relationships, some of which may not be easily verifiable.

3) Artificial intelligence approach

Many of the limitations faced by the analytical and statistical approaches can be resolved by using artificial intelligence approaches. The approach offers a good way of treating the data that can be rather spurious and where clear understanding of the nature of the data is lacking. A number of artificial intelligence approaches have been used in domain formulation, for example fuzzy logic (Kao et al., 2007), neural network (Pietrzykowski and Uriasz, 2004, 2008, 2009, Zhu et al., 2001).
Chapter Three: Model Formulation

Artificial Intelligence approaches have the advantages of formulating the inference rules without prior knowledge and allow modeling the learning process to derive the final outcome. The main disadvantage lies in having sufficient number of learning sets and defining the terminating criteria for converged results. In addition when the the number of factors are high, these approaches require considerable computation time, especially if a high number of iterations are needed. There is also a concern that the calibrated model may not be the best fitted or indeed well fitted.

In considering the different approaches in dealing with the data and in calibrating the model, formulation using an analytical model is likely to be limited. Statistical approaches require good understanding of the nature of the dataset which can be problematic. Hence given the multiple unknowns in the relationships and the data, the artificial intelligence approaches may be the most useful approach to calibrate the domain model.

3.4.2 Model Formulation in Mathematical Form

This section describes how the model is formulated in the mathematical form suitable for calibration using the artificial intelligence approach. The formulation process includes three components: the representation of domain shape, the representation of the basic domain size for stationary ship and finally the effect of ship speed function.

Consider an encounter between a pair of ships in close proximity. Assume that each ship maintain an individual ship domain and that for safe navigation, the two domains will not overlap. It is further assumed that the size of the individual domain
is governed by the ship size and speed.

Further consider the individual domain is defined in the shape of asymmetrical polygon with \( n \) number of vertices and that the boundary of the domain is formed by joining the \( n \) vertices sequentially. The size of the polygon is measured by the radial distance, \( R \) from the ship centre to the different vertices of the polygon, defined by an polar angle \( \theta_i \) clockwise from the ship heading and it is governed by a function of ship length (\( L \)) and speed (\( v \)):

\[
R_{\theta_i} = \alpha_{\theta_i} \cdot L \cdot g_{\theta_i}(v) \tag{3.11}
\]

where \( i \) (\( i = 1, ..., n \)) is the indicator of vertex, and \( n \) is the total number of vertices based on specified angular interval discretization \( \Delta \) (in degrees) such that \( n = \frac{360}{\Delta} \); \( \alpha_{\theta_i} \) the normalized radial distance of the domain when the vessel is stationary at the polar angle \( \theta_i \); \( g_{\theta_i}(v) \) is a speed function which governs how the domain is expanded with non-zero value of \( v \) at the polar angle \( \theta_i \) and this will be formulated in Section 3.4.2.1. This formulation is shown graphically in Figure 3.9.

![Figure 3.9 Representation of Ship Domain](image-url)
The vector $\alpha$, representing the normalized zero-speed domain as shown in Figure 3.10 is to be calibrated along with parameters defined in the speed function.

![Figure 3.10 Representation of Zero-speed Domain](image)

Note that as a normalized vector, $\alpha$ explains the shape of the ship domain and by assuming that the ship domain of any ship is proportional to the Length Overall (LOA), the size of the domain can also be determined. It is further assumed that while $\alpha$ is assumed well defined and invariant to other factors, a different vector may be derived for different environmental conditions. For example, a different set of $\alpha$ values will be obtained for the day and night conditions.

In addition, the formulation of ship domain model will be further modified by including a normalized stochastic element to account for variations in perceiving ship domains among navigators. This will be discussed in Section 5.4.

### 3.4.2.1 Speed function in ship domain model

Compared to the shape parameter in the ship domain, the speed function in the
equation serves as a size adjustment for scaling up the zero-speed ship domain. Fundamentally, it is possible to define the speed function for every direction $\theta$. However, this will add unnecessary complexity to the model and the increase in degrees of freedom will introduce more noise effects. Instead, the speed functions are specified only for axial directions and the speed component for other directions are interpolated based on calibrated speed functions in the axial directions. The methodology is illustrated as follows.

Suppose that the speed functions for four axial directions, i.e., fore, aft, port and starboard sides are defined as $g_f(v)$, $g_a(v)$, $g_p(v)$ and $g_s(v)$ respectively. The effect of speed on ship domain is generally non-linear, with the domain size increasing with speed initially but tapering off at higher speeds. A suitable formulation of the speed function would be the modified quadratic function as

$$g(v) = 1 + \lambda v + \mu v^2$$  \hspace{1cm} (3.12)

in which $\lambda$ and $\mu$ are the parameters to be determined. Allowing different speed functions for the four axial axes will result in eight degrees of freedom, i.e., eight calibration parameters $\lambda_f, \mu_f, \lambda_a, \mu_a, \lambda_p, \mu_p, \lambda_s, \mu_s$.

Further, the speed function in any given heading $\theta$ is obtained by interpolating the calibrated functions above following elliptical curves as

$$g_\theta = \frac{\left[ (1 + m)g_f + (1 - m)g_a \right]}{2\sqrt{\left[ (1 + m)g_f \sin \theta + (1 - m)g_a \sin \theta \right]^2 + \left[ (1 + n)g_p \cos \theta + (1 - n)g_s \cos \theta \right]^2}}$$  \hspace{1cm} (3.13)
where $g_\theta$ is a short form of $g_\theta(v)$, $g_f$, $g_s$, $g_a$ and $g_p$ are the short form of $g_f(v)$, $g_s(v)$ and $g_a(v)$. The sign values of $m$ and $n$ are defined as

\[
m = \begin{cases} 
1 & \theta \in [-\pi/2, \pi/2) \\
-1 & \theta \in [-\pi, \pi/2) \cup [\pi/2, \pi) 
\end{cases}
\]  

(3.14)

\[
n = \begin{cases} 
1 & \theta \in [0, \pi) \\
-1 & \theta \in [-\pi, 0) 
\end{cases}
\]  

(3.15)

The relationship between the value of the speed function in any direction and values in the four axial directions follow elliptical curves as shown in Figure 3.11.

![Figure 3.11 Formulation of Speed Function $g_\theta(v)$ by Interpolation](image)

### 3.5 SUMMARY

In this chapter, the necessity to build a model of ship domain is enhanced by comparing it with other collision risk measures. Based on the comprehensive and critical reviews on ship domains, a conceptual model is proposed by understanding ship domains. The model, consists of two individual domains, interactively takes
into account the ship attributes, including ship LOA and speed of both OS and TS. By summing up the two domains according to their relative bearing and heading difference, the encounter type has been considered in more generalized manner which also contributes to a dynamic model. The polygonal shape domain with small discretized angular interval offers a higher degree of freedom to model interactions between ships more correctly. The involvement of the stochastic element in the model allows variations in perceiving the spatial separation from navigators.

The conceptual domain is further formulated as a mathematical model by taking into account ship size and ship speed as well as a human factor component. In formulating the model, parameters have been assumed and expected to be different under conditions of different visibility. These parameters will be determined by designing a systematic calibration method and using traffic movement data in Chapter four.
4.1 INTRODUCTION

In this chapter, the proposed model of ship domain is calibrated using traffic movement data from Singapore Port covering day and night time. The traffic data are prepared in the form of encounters involving two ships in close proximity. An iterative optimization process for deriving the necessary model parameters is proposed due to the characteristics of the traffic encounters contributing to ship domain. The optimization method is solved by a Genetic Algorithm (GA), which has the advantage of converging faster and reducing random effects. The day-time and night-time domains are calibrated separately and compared. Finally, the domain model is evaluated in the aspects of fitness and reliability.

4.2 DATA COLLECTION AND PREPARATION

4.2.1 Data Collection

The traffic movement data are obtained from the Vessel Traffic Information System (VTIS) database of Singapore port and straits as shown in Figure 4.1. The data include the vessel’s positions in coordinates, speeds, headings and their ship attributes, i.e., ship length, draft, and the Maritime Mobile Service Identity (MMSI) number representing the identity of ships. The kinematic information of ship
movement is usually updated every two seconds depending on traffic characteristics so that detailed information of the vessel trajectories are possible.

![Map of Singapore Port Waters](image)

**Figure 4.1 Location of Singapore Port Waters Around Singapore**

### 4.2.2 Data Preparation

The collected traffic movement data would be cleaned by excluding some extreme cases and noises. It is followed by restructuring traffic movement data into ship encounters for calibration purpose subsequently.

#### 4.2.2.1 Data Cleansing

To obtain a clean dataset, data arising from the following situations are excluded:

- Ships sailing at the speed exceeding 35 knots which is regarded unrealistic in restricted waters;
- Ships sailing at near zero speed because they are identified as ships anchoring or mooring either within or outside anchorages; this group of ships are also characterized by frequent varying ship heading due to the influence...
of wind and current;

- Ships with special missions which probably do not obey the traffic rules and maintain closeness to other ships; these ships covering 3% of the total ships, include tug boat, towing ship, pilot ship, Search and Rescue (SAR), coast police patrols or bunkering ships, etc

- Ship’s MMSI number or major attributes (for example, ship length or speed) are partly missing (about 10% of identified ships); these ships are mainly small ships, for example, fishing ships and yachts, sailing in confined low-depth waters and inland waterways.

After cleaning the traffic data, the histogram chart of the distribution of ship LOA is plotted in the Figure 4.2. Since no significant difference is identified to ship LOA in the daytime and nighttime, the total 624 ships are accumulated and distributed over a range of 400m in ship length. The figure shows that about 66% of ships have a LOA between 50m and 200m and the mean of ship LOA is 133m. In addition, the probability density of ship speed is also plotted separately for daytime and nighttime. By removing around 25% of situations when ships are stationery or near stationery, the ship speeds are widely spread out between 2 to 32 knots. The figure shows that the mean of ship speed in the daytime is higher than that in the nighttime as indicated in the Figure 4.3.
4.2.2 Preliminary Identification of Encounter

To calibrate the parameters in the model, the encounter needs to be identified involving two ships in a close range with certain relative bearing and heading difference. For this reason, the traffic movement data prepared in previous section should be restructured in the form of encounter. The algorithm of transforming the traffic movement data into ship encounter is formulated as follows.
The two ships involved in an encounter are denoted by own ship (OS) and target ship (TS) respectively as seen in Figure 4.4. The instant position of OS and TS is denoted in $x$ and $y$ coordinate. For each pair of identified OS and TS, the center distance between them by

$$d_{o,T} = \sqrt{(x_o - x_t)^2 + (y_o - y_t)^2}$$  \hspace{1cm} (4.1)$$

where $(x_o, y_o)$ and $(x_t, y_t)$ are the gravity center of OS and TS respectively. For each $d_{o,T} \leq r_s$, in which $r_s$ (assumed 2 n.m. in this research) is the radius of circular range, the pair of ship should be selected as a potential encounter. The relative bearing and heading difference between this pair of ship can be calculated by

$$\delta_{o,T} = \arcsin \frac{|x_o - x_t|}{d_{o,T}}$$  \hspace{1cm} (4.2)$$

$$\theta_{o,T} = |\theta_o - \theta_t|$$  \hspace{1cm} (4.3)$$

where $\delta_{o,T} \in (-\pi, \pi]$ is the relative bearing of TS to OS, $\theta_{o,T} \in (-\pi, \pi]$ is the heading difference between OS and TS; $\theta_o$ and $\theta_t$ are the heading of OS and TS where $\theta_o \in (-\pi, \pi]$, and $\theta_t \in (-\pi, \pi]$. The relative bearing and the ship heading are defined to be positive in clockwise direction and negative in the anti-clockwise direction with respect to the true north direction as seen in Figure 4.4.
4.3 CALIBRATION OF SHIP DOMAIN

This section addresses the calibration process for the ship domain model using the prepared traffic encounters. Before the calibration process, a comprehensive review of the concept of ship domain and the way it is determined using traffic movement data is first undertaken. Based on the understanding of the data and the characteristics of the proposed model, an iterative calibration method is then proposed. The model parameters are further estimated by employing the optimization technique of GA.

4.3.1 Review of Concept of Ship Domain

The existing methods of determining the ship domain focus on examining the traffic distribution around a central vessel with and without the presence of such a domain.
Chapter Four: Model Calibration & Evaluation

The boundary of the ship domain was assumed to locate at the place where the local maximum of the traffic density is (Fujii and Tanaka, 1971, Coldwell, 1983), as shown in Figure 4.5.

![Figure 4.5 Method of Determining Ship Domain based on Assumed Traffic Distribution (Coldwell, 1983)](image)

Goodwin (1975) assumed the domain is defined at the position where the number of ships identified outnumber the expected number of ships without the effect of the ship domain as shown in Figure 4.6. If there is no ship domain, the traffic is assumed uniformly distributed around a central ship but with the presence of a ship domain, the distribution of the ships around the subject ship will be disturbed. This applies logical but the method still relies on the need for a uniform distribution of
ships beyond the immediate vicinity of the subject ship and this may not be achieved especially among encounters in close waters.

While the methods of Coldwell and Goodwin have their merits, they are not entirely suitable for close waters encounters. Instead, this research will propose an innovative method, which is described in the following section.

**4.3.2 Iterative Calibration Process**

Before calibrating the parameters in the ship domain, several important issues should be mentioned. First, ships nearer the subject ship are more likely to be influenced by the ship domain than ships further away. This means that the probability that an encounter pair will contribute to the ship domain computation will decrease with increased space separation, vanishing quickly with distance apart. However, the effect of this cannot be determined as *a priori* since the ship domain has still to be determined. Second, taking into account the variation in ship types, ship sizes, maneuvering speeds as well as encounter types, the space domain for
each ship pair will not be a static constant, for example, 2 n.m. away in the previous Section 4.2.1.3, but a variable dependent on the characteristics of the encounter. This means that since the size of ship domain is unknown, an iterative process will need to be adopted to satisfy all the conditions. Third, as developed in Chapter 3, the two set of parameters in the domain model, i.e., the parameters for zero-speed domain and the parameters in the speed function are likely to be interrelated. Hence in order to limit the interactions between these two set of parameters, an iterative calibration process is needed.

The structure of the iterative calibration method is presented in a flow chart shown in Figure 4.7.

---

**Figure 4.7 Flow Chart of Iterative Calibration Method**
At the initial stage, the shape and size of the ship domain is unknown. However there is still need to extract close encounters based on certain criterion for calibration purpose. Therefore, as a component of initial setup, the extraction criterion is defined as a circular range with a radius of 7·LOA which is decided according to the domain developed by Fujii and Tanaka (1971). In addition, to initiate the iterative calibration process, an initial zero-speed domain should also be assumed. A circular domain with a radius of one LOA of the ship is assumed in this research from the idea of swing circle in ship anchoring. With the initial setup and the extracted close encounters, the speed function and zero-speed domain are sequentially calibrated. The estimations of the parameters in the speed function and in the zero-speed domain are conducted separately due to the interrelated nature of two set of parameters.

In the following iterations, the close encounters are re-extracted from the preliminary prepared database based on the updated ship domain model. The criterion for extraction of close encounters is also redefined. It is assumed that the encounter with a distance which is less than 1.5 times of the ship domain will be chosen as the close encounters for subsequent iteration. It will be then checked by termination condition to be defined in the subsequent section. If the termination condition is unsatisfied, the next iteration of optimization should be conducted. In order to speed up the iterative optimization process, the zero-speed domain in this iteration is assumed to be same as that updated in the previous iteration. The iterative calibration process will not stop until the termination condition is satisfied and then the calibrated parameters in the ship domain model can be output.
4.3.2.1 Parameter estimation

The process of parameter estimation indicated in Figure 4.6 will be discussed in this section. Given the extracted close encounters, the model’s parameter values can be estimated such that the distance between the model behavior and the data is minimal. Therefore, an optimization problem is formulated for estimating the parameters in the domain model.

The parameter estimation process is formulated as a constrained optimization problem such as

\[
\text{Minimize: } F_n (\alpha_i, \lambda_i, \mu_i)
\]

\[
\text{Subject to: } \alpha_i > 0; \\
\lambda_i + 2\mu_i v_{\text{max}} > 0; \\
\lambda_i > 0; \\
\mu_i < 0.
\]

where, \( F_n \) stands for the objective function of the optimization problem involving two sets of parameters; \( \alpha_i \) are a set of parameters governing the zero-speed domain, in which \( k = 1, 2, \ldots, 2\pi/\Delta \) and \( \Delta \) is the angular discretization interval; \( \lambda_i \) and \( \mu_i \) is the parameters in the speed function in which \( x = f, a, p, s \) representing the fore, aft, port and starboard side; \( v_{\text{max}} \) is the maximum achievable speed. Since the speed function is assumed to follow quadratic function defined in Section 3.4.2.1, it is necessary to constrain the parameters of the function so that the values of the speed function will not decrease with increasing speed. Therefore, the parameters in the
speed function are under the constraint specified and lower and/or upper bound limits.

Now the problem is to define an objective function to estimate the model parameters. As mentioned before, the objective is to minimize the difference between the effective clear areas described by the proposed model and the data showing the actual space separation between ships. The difference between them can be treated as an error function defined as

\[ E = d - SD_{os} - SD_{ts} \] 

(4.2)

where \(d\) is the actual distance between ships; \(SD_{os}\) and \(SD_{ts}\) are the length of the line connecting the center of the two ships inside the respective ship domain envelopes as shown in Figure 4.8. The summation of the \(SD_{os}\) and \(SD_{ts}\) is defined as the required space separation determined by two individual ship domains.

---

**Figure 4.8 Illustration of Variables Defined in Error Function**
Then the relative error can be calculated following the general formula as

$$E_{rel} = \frac{|E|}{d} = \frac{|d - SD_{os} - SD_{ts}|}{d}$$  \hspace{1cm} (4.3)

where $E_{rel}$ is the relative error to be used in the objective function. This is because the error itself may increase or decrease proportionally to the distance between ships. For an encounter which is further way, it is expected that the estimation error of the ship domain is higher than that of a closer encounter. It may lead to bias by treating the estimation errors equally for encounters of different space separations. Therefore, for an encounter which is further away, the increased error of estimation will be compensated by employing the measure of the relative error.

If the objective function is defined by summing up the relative errors of all the identified encounters, it means all the encounters equally contribute to the formulation of the ship domain. The assumption is probably invalid because in general, the ships nearer the domain of OS are more likely to be influenced by the ship domain than ships which are further away. Therefore, to model the contribution of encounter to ship domain, a weight function is employed and defined by a modified exponential function as

$$w(E) = \begin{cases} 
e^{-\omega E} & E \geq 0 \\ 1 & E < 0 \end{cases}$$  \hspace{1cm} (4.4)

where $\omega$ is the parameter of the exponential function. The determination of this parameter in the weight function will be discussed in the Section 4.3.2.2. In this

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research, encounters resulting in $E < 0$ are assumed to fall into the restricted zone and encounters with $E \geq 0$ are located at the buffer zone. In Equation 4.4, on the one hand, the encounters located at the restricted zone will be given equal weights to avoid overdependence on the extreme encounters in determining the ship domain. On the other hand, the encounters located at the buffer zone are weighted exponentially, because as the error value increases, the chance of the encounter contributing the determination of the domain is slimmer. Therefore, for the encounter with very large value of error, it will be of no significance to the ship domain.

Finally, the objective function for determining the ship domain is defined as the sum of the weighted relative error for each encounter involving a pair of ship $i$ and ship $j$ as

$$
\sum E_{ni} \cdot w(E) = \sum \frac{d_y - SD_i - SD_j}{d_y} \cdot w(d_y - SD_j - SD_i)
$$

(4.5)

where $SD_i$ is the length of the line connecting the centre of ship $i$ and ship $j$ within the domain of the ship $i$ and $SD_j = \alpha_{\theta_i} g_{\theta_i}(v)L_i$ in which $L_i$ is the LOA of the ship $i$; $SD_j$ is the length of the line connecting the centre of ship $j$ and ship $i$ within the domain of ship $j$ and $SD_i = \alpha_{\theta_j} g_{\theta_j}(v)L_j$ in which $L_j$ is the LOA of the ship $j$; $d_y$ is the distance between ship $i$ and ship $j$; $\alpha_{\theta_i}$ and $\alpha_{\theta_j}$ are the parameters in the zero-speed domain on the relative bearing of $\theta_i$ and $\theta_j$; $g_{\theta_i}(v), g_{\theta_j}(v)$ is the speed functions on the relative bearing of $\theta_i$ and $\theta_j$; $g_{\theta_i}(v)$ is defined based on the four
axial directions of \( g(v) = 1 + \lambda v + \mu v^2 \) in Section 3.4.2.1 previously.

### 4.3.2.2 Determination of weight function

In previous section, an exponential weight function is defined for representing the probability of an encounter in contributing to the ship domain. The parameter \( \omega \) in the exponential function affecting the performance of the calibration process will be determined in this section.

As indicated in the equation 4.4, the weight function with higher value of \( \omega \) will exclude many encounters further away and over-dependence on the closer encounter. This will result in higher chance of excluding significant encounter and increase uncertainty of estimation. On the other hand, the weight function with lower value of \( \omega \) will include more non-significant encounter and increase the inaccuracy of the model calibration. Therefore, an appropriate parameter needs to be determined based on certain criterion. This research employs a criterion defined by the percentage of encounters falling into the restricted zone among all the weighted encounters as

\[
\frac{N(E < 0)}{N(w(E) > \varepsilon)} \times 100 \% \tag{4.6}
\]

where \( N(E < 0) \) denotes the amount of encounters falling into the restricted zone, and \( N(w(E) > \varepsilon) \) represents the amount of encounters that are weighted more than \( \varepsilon \) which is the minimum value of weights that is assumed to be practical.
Figure 4.9 Selection of Weight Parameter Based on Proposed Criterion

For weight function with various values of $\omega$, the optimization algorithm for calibrating domain model is conducted and the values of this criterion are computed accordingly. The change of values of the proposed criterion with respect to different parameters in the weight function is presented in Figure 4.9. It shows that with the increase of parameter, the criterion value decrease first and then goes up. Therefore, there is a minimum value for the criterion value and the corresponding optimal parameter of exponential function can be selected. From the Figure 4.9, the weight parameter of $\omega = 3.5$ is approximately selected as the most reasonable parameter.

4.3.3 Optimization using GA

The optimization problem defined in previous section will be solved using optimization technique of Genetic Algorithm (GA) in this section. Due to the highly interactive nature of the parameters, the two set of parameters are calibrated iteratively using GA. The implementation of GA in this research is coded under the programming environment of MATLAB. The Global Optimization Toolbox in
MATLAB provides various methods in searching for global solutions including the GA. The toolbox also allows customization by users’ purpose. Therefore, for this specific optimization problem, certain aspects related to GA algorithm need to be specified as follows.

### 4.3.3.1 Optimization problem under linear constraints

This research requires dealing with the optimization problem under linear constraints. GAs are directly applicable only to unconstrained optimization problems; thus it requires special mechanisms to incorporate the constraints into the evolutionary process. One group of methods adopts the concept of convex spaces to maintain all the individuals in the feasible region. The method could be applicable to any optimization problem with linear constraints. However, it is not suitable to optimization problems with non-linear constraints, and requires an initial feasible population, which may not be easily obtained. The alternative approach in dealing with non-linear constraints is to introduce a cost function that penalizes the individuals that are outside the feasible region. Although a variety of penalty functions have been invented, the difficulties lie in determining appropriate values of the penalty parameters. This requires users to conduct experiments with different penalty parameters and decide based on the results and expert judgment. To avoid the troublesome, this research adopts the first group of methods in solving the optimization problem. The way the GA in MATLAB satisfies the linear and bound constraints is to use crossover and mutation functions that only generate feasible points satisfying linear constraints and limits of variables.
4.3.3.2 Initial population

The first step in the functioning of a GA is, the generation of an initial population. One of the most important factors that determine the performance of the GA is the diversity of the population. Two issues affecting the diversity of the initial population are the size of the population and method of generating the population.

The population size depends on the nature especially the difficulty of the problem (Harik and Lobo, 1999). It is widely agreed that a “small” population size could result in poor solutions (Piszcz and Soule, 2006); a too “large” population size require more computation time in seeking for an optimal solution (Lobo and Goldberg, 2004). In addition, the increase population size may lead difficulty in finding good solutions which can occur in problems where variable are dependent.

In this research, for optimizing parameters of the zero-domain, the number of variable is 36 assuming the discretization step of $10^{-3}$; for the optimization of speed function, 8 variables in total are used for four directions. Therefore, the corresponding population size is chosen of 40 and 20 respectively.

Besides, the method of generating the initial population is of great importance in the GA performance. Traditionally, the population is generated randomly, allowing the entire range of possible solutions in the search space. However, if the problem is quite difficult, information regarding the possible solution can be utilized to seed the GA. A measure of diversity could be good in terms of performance of the algorithm (Burke et al., 2004). Not only used to generate the initial population, the diversity is also employed as a way to guide the algorithm to avoid premature convergence (Yee
et al., 1997). If the diversity is too high or too low, the genetic algorithm might not perform well; thus a trade-off problem arises regarding the diversity of the population. In MATLAB, the plot of average distance could represent the diversity of the population for each generation. The diversity is controlled by setting the initial range within which the initial population is generated using a random number generator.

In this research, due to the large numbers of variables (for example, 36 variables) in the optimization for zero-speed domain, it is difficult to achieve good solutions especially under linear constraints. Therefore, the initial population for the optimization for zero-speed domain is generated in a pseudo-random way. To generate possible solutions for the initial population, circular domains are firstly created and then randomly modified within a small range of variations. The radius of the domain could be uniformly generated within a specified range. The generated individuals are feasible solutions in accordance to the constraints of the shape parameters. Besides the seeded individuals, the rest population is randomly generated. However, this portion of population may not be feasible due to the constraints.

4.3.3.3 Selection operator

During each generation, the individuals in the population are evaluated using fitness function and a proportion of the population is selected to breed a new generation. The selection process is based on the fitness value, and fitter solutions are typically more likely to be selected. Several selection options are available in MATLAB toolbox. The default selection option, Stochastic uniform, lays out a line in which
each parent corresponds to a section of the line of length proportional to its scaled value. The algorithm moves along the line in steps of equal size. At each step, the algorithm allocates a parent from the section it lands on. In this research, we chose the default selection option.

4.3.3.4 Crossover operator

Genetic operators are utilized to reproduce the following generation of populations. As a main operator, the crossover is a process of taking more than one parent solutions and producing a child solution from them. The implementation of the crossover is governed by one major parameter, defined as the crossover fraction. It specifies the fraction of each population, other than the elite children, to be made up of crossover solutions. The elite children are the individual with the best fitness value in the current generation that is guaranteed to survive to the next generation. The crossover fraction of 0 means all the population other than the elite children will be possibly mutated and the fraction of 1 assumes all the population will be considered as parents for crossover implementation. The default value of the crossover fraction is 0.8; however, for different fitness functions and optimization problem, a different setting for crossover fraction are expected.

In this research, an experiment is conducted to find out the best suitable crossover fraction. The Figure 4.10 shows the means, median, 25th and 75th percentiles of the best fitness value over 5 generations, with respect to the crossover fraction. Based on this experiment, the crossover fraction in this study is chosen as 0.4.
In addition to the fraction of crossover, the type of crossover is also important especially when dealing with optimization problem under constraints. Various options of crossover operators are given in MATLAB including ‘Scattered’, ‘Single point’, ‘Two point’, ‘Intermediate’, ‘Heuristic’, ‘Arithmetic’ and customized operators by users. Among them, the ‘Arithmetic’ is adopted because it is the most suited operator for optimization with linear constraints. It creates children that are the weighted arithmetic mean of two parents; therefore the children are always feasible with respect to linear constraints and bounds. Some other operators have also been designed for optimization under constraints (Ortiz-Boyer et al., 2002) may deserve further researches.

4.3.3.5 Mutation operator

Mutation operator specifies how the genetic algorithm makes small random changes in the individuals in the population to create mutation children. The mutation
operator is vital to preserve and introduce diversity to GAs from one generation to the next. A common method of implementing the mutation operator involves generating a random variable for each bit in a sequence. This random variable tells whether or not a particular bit will be modified. This mutation procedure, based on the biological point mutation, is called single point mutation. The default mutation option in MATLAB is ‘Gaussian’, in which the amount of mutation is proportional to the standard deviation of the distribution, decreases at each new generation. The average amount of mutation in each generation is governed by two parameters, i.e., the Scale and Shrink options. The Scale controls the standard deviation of the mutation at the first generation and the Shrink controls the rate at which the average amount of mutation decreases. However, the ‘Gaussian’ operator cannot guarantee the mutated individual will meet the linear constraints in the problem. Therefore in this research, an alternative option for mutation operator is chosen, i.e., the ‘Adaptive Feasible’ mutation. The operator allows randomly generating directions that are adaptive with respect to last generation, and a step length on the chosen direction is selected so that linear constraints and bounds are satisfied. Since the optimization problem in this research is under linear constrains, the ‘Adaptive Feasible’ mutation is chosen.

4.3.3.6 Stopping criteria

The iterative process is terminated until any of the stopping criteria is satisfied. Typical stopping criteria include:

- The maximum number of iterations for the genetic algorithm is reached;
- The weighted average change in the fitness function is less than the predefined Function Tolerance;
• The maximum time for optimization has been run out;
• The best fitness value is less than or equal to the value of predefined fitness limit;
• There is no improvement in the best fitness value for an interval of time specified by Stall time;
• The cumulative change in the fitness function value is less than or equal to Function Tolerance.

![Graph showing fitness values over generations](image)

**Figure 4.11 Selection of Stopping Criterion for Optimization**

Increasing the number of generations often improves the final solutions. To determine a suitable criterion for terminating the iteration, a running for the optimization process is conducted. The Figure 4.11 indicates after the iteration 150, the algorithm stops since the weighted average change in the fitness function values over the last 50 generation is less than function tolerance defined in GA. The fitness values evaluated here include the best fitness and the mean fitness.
4.3.4 Results of Model Calibration

The calibrated domain model in the daytime and nighttime include the zero-speed domains shown in Figure 4.12 and speed functions for the four major directions in Figure 4.13 respectively. The Figure 4.12 shows that the zero-speed domains in the daytime (a) and nighttime (b) are quite rounded and the sizes are quite similar. Comparing the speed functions shown in Figure 4.13, the values of the speed function for different speeds in the nighttime domain are almost the same as those in the daytime domain in the port, starboard and aft sides. However, for the fore direction, the value of the speed function in the nighttime domain is significantly greater than that in the daytime. It shows that navigators at night are more conservative in judging the ship domain especially in the fore direction. In addition, the domain enlarges significantly with travel speed suggest that navigators are more sensitive to speed at night although the speeds are often reduced at night.

Moreover, the value of the speed function in the fore direction is the highest and about 7.2 at the speed of 30 knots in the daytime as shown in Figure 4.13 (a). This value is quite similar to Fujii’s domain (1971). The values of the speed function in the port and starboard side are about 3 at 30 knots which are again consistent to the Fujii’s domain. Further comparisons between the calibrated domain model and other existing models will be conducted in Chapter 5.
4.4 EVALUATION OF DOMAIN MODEL

The evaluation of the calibration model of the ship domain involves two major parts: evaluating the fitness of a model and assessing the reliability of the model. Due to the iterative feature of the calibration process, the fitness of the model is evaluated by investigating the stopping criterion. The reliability of the model is evaluated by...
examining the calibrated domain for different sectors, speeds and for daytime and nighttime.

4.4.1 Evaluation of Fitness

In this research, the close encounters have been iteratively selected as the dataset for calibrating the parameters in the domain model. The space separation under these close encounters may not necessarily observe the required safe distance governed by the domain model. Therefore, the standard method of evaluating the fitness of the model, such as the goodness-of-fit statistics may not be suitable. Instead, this research employs an innovative method for evaluation of the fitness.

Based on iterative process of calibration, the stopping criterion is used to assess the fitness of the domain model. The stopping criterion is defined previously as the percentage change of the amount of encounters extracted for calibrating the domain model. It is trustworthy to believe that after certain iterations, the model can be assumed to be sufficiently fit.

The amount of encounters taken into account in each iteration in the daytime (a) and nighttime (b) are shown in the Figure 4.14.

From Figure 4.14, the iterative optimization process could stop at the fifth iteration for the day time and third iteration for the night time, because the percentage difference in the number of encounters is less than 4% for domains in both day/night conditions. There is no need to conduct more iteration because the improvement of model calibration will be negligible.
4.4.2 Evaluation of Reliability

The reliability of the calibration model is evaluated by first investigating how significantly the model is affected by data distribution for different sectors of the ship domain. It is assumed that the domain sector with more encounters is likely to be estimated more accurately, and the sector with fewer points may involve more uncertainty. The amount of encounters in each sector, which is defined by the relative bearing at the center of the sector, are shown in Figure 4.15 in the daytime and Figure 4.16 in the nighttime. The encounters are distinguished by encounter in restricted zone and encounters in buffer zone. It can be seen from the figures that the fore and astern sides have more encounters than the port and starboard sides have.
Similarly, the reliability of estimated domain is also related to the amount of ships for each speed band with speed interval of 1 knots. The Figure 4.17 and Figure 4.18 show the amount of encounters in restricted zone and that in buffer zone for each speed band in the daytime and nighttime respectively. It can be seen from the figures that a large amount of encounters involve ships traveling at speed between 7 to 16 knots in the daytime while in the nighttime, many ships sail at a speed of 9 to 13 knots.
Further, the reliability of estimating the ship domain is evaluated by employing the criterion of standard error of mean. The standard error of the mean is a general measure of the accuracy of predictions which is defined by standard deviation divided by the square root of the sample size, such as

\[
SE = \frac{\sigma}{\sqrt{n_{SE}}}
\]  

(4.7)

where \( SE \) is the standard error, \( \sigma \) is standard deviation of the population and \( n_{SE} \) is
the sample size.

To examine the reliability of domain estimation, it is necessary to separate the error of an encounter $E$ defined in Equation 4.2 for the pair of ships. Therefore, the errors of OS and TS are obtained by proportionally distributing the total error of an encounter based on the size of the ship domain as OS and TS as

$$\frac{E_{os}}{SD_{os}} = \frac{E_{ts}}{SD_{ts}} = \frac{E}{SD} \quad (4.8)$$

where $E_{os}$ and $E_{ts}$ are the errors due to OS and TS respectively; $SD$ is the required safe distance of the encounter which is the sum of $SD_{os}$ and $SD_{ts}$ in the line connecting the centers of OS and TS; $SD_{os}$ and $SD_{ts}$ are determined by the individual ship domains.

Then the standard errors of the mean of the error percentage given by $\% E = \frac{E}{SD}$ can be computed for each sector of the domain and speed band. Finally, with the computed standard errors of percentage error for each sector of the domain, the ship domain with one standard error (denoted as $SD_{SE}$) in the restricted zone and buffer zone and the estimated domain from the model at ship speed of 12 knots are outlined in Figure 4.19. The figure shows there are larger standard errors on the port and starboard sides than on the fore and stern sides, which can be explained due to the unbalanced distributions of the number of encounters in each sector as shown in Figure 4.16.
The reliability of the ship domain is also assessed against different speed bands. Figure 4.20 outlined the domains with one standard error at speed band of (a) 9 knots and (b) 12 knots in the nighttime. It is obvious that the domain with one standard error at the speed band of 9 knots has more deviations than that at the speed band of 12 knots. This effect can be similarly explained by the variations in the number of encounters with speeds of 9 knots and 12 knots shown in Figure 4.18.
Figure 4.20 Domains with One standard error for different speed bands

Figure 4.21 Domains with One Standard Error in Daytime/ Nighttime
In addition, the differences in the domains with one standard error in the daytime and nighttime are shown in Figure 4.21. The domain at 9 knots in the nighttime has more deviations than that in the daytime. This suggests the domain calibrated for the nighttime is less reliable compared to that of the daytime. This is probably due to the restricted visibility in the nighttime which governs the navigation behavior.

4.5 SUMMARY

The proposed model of ship domain has been calibrated using traffic movement data in this chapter. The extracted traffic movement data have been restructured into the form of encounter in close vicinity involving two encountering ships. An iterative calibration method has been proposed to re-extract the close encounters based on the updated ship domain model. The two set of parameters in the domain model are calibrated sequentially and iteratively due to the highly interactive nature between the zero-speed domain and the speed function. The iterative calibration process terminates when sufficient fitness of the model is achieved. It is found that after five iterations for the domain in the daytime and four iterations for the domain in the nighttime, the model can be well calibrated with good fitness. The reliability evaluation of the model reveals that the models with following features are more reliable: 1) domain sectors in the fore and aft side; 2) speed band with more encounters i.e., 12 knots in the nighttime and 3) daytime domain over nighttime domain. The results of the calibrated domain seem reasonable in accordance with Fujii’s model (1971) and more comparisons with existing domain models will be conducted in Chapter 5.
CHAPTER FIVE
INTERPRETATION OF SHIP DOMAIN MODEL

5.1 INTRODUCTION

In this chapter, the proposed and calibrated ship domain model will be interpreted in the following aspects. First, the ship domains will be compared with those of existing models using examples of different ship sizes, sailing speeds and encounters. The advantages of the proposed domain model over existing domain models will be discussed. Five case studies of specific encounters will be conducted to examine the influence of ship domains on the situations where a collision avoidance action is necessary. In addition, the ability of the proposed model to take into account perceptual differences among navigators will be expounded.

5.2 COMPARISONS OF SHIP DOMAINS

This section compares the proposed ship domain with those from selected earlier studies, which generally represent the range of ship domain models in literature. As some previous work considers ship domain around a single ship, i.e., the OS or the TS while this study considers the summation of two individual ship domains around the OS and TS respectively, the equivalent single domain of a moving OS and a stationary TS is computed for the purpose of comparison. For some research work that considers attributes of both OS and TS, the comparison is based on a pair of moving OS and TS.
Consider a basic situation of a moving OS and stationary TS with particular ship attributes specified in Table 5.1.

| Table 5.1 Ship Attributes of Moving OS and Stationary TS in Basic Situation |
|-----------------------------|---|---|
| LOA (m)        | OS | TS |
| 200            |    | 200|
| Speed (knots)  | 15 | 0  |
| Heading (degree)| 0  | -  |

Note: TS is stationary therefore no heading of TS is available.

5.2.1 Comparisons with Domains based on Single Ship

1) Comparison with circular-type domains based on attributes of single ship

Figure 5.1 shows the circular-type ship domain of Goodwin (1975). It has three unequal sectors with different radii, which are invariant with ship speed and length. The proposed equivalent single domain for the moving OS and stationary TS as in the basic case is superimposed as a solid line. In the figures for domain comparison in this chapter, the ship domain developed by this research is denoted as SD in the legend.

There are clearly distinctive differences between the proposed ship domain and Goodwin’s model. Goodwin’s model oversimplifies the space domain with large discontinuities at the sector boundaries. In addition, Goodwin’s model overestimates the space requirements, particularly on the port and starboard sides.

There is however, closer similarity along the longitudinal axis. Nevertheless, this is
incidental since Goodwin’s model does not account for the size of the ships and the speeds. Hence while for the basic case, the stern side but not the fore side of Goodwin’s model may match the proposed domain, the fore side of Goodwin’s model may be a better match with the proposed model for a larger and faster OS (LOA = 250m, speed = 20knots) as shown in the Figure 5.1.

It may be concluded that as an invariant and simplistic model, Goodwin’s ship domain is suitable for large and fast vessels and as such will cater for most ship domains, albeit that slower and smaller vessels will be highly overestimated.

2) Comparison with hexagonal-type domains on attributes of single ship

The vertices of the irregular hexagonal shape domain of Smierzchalski (2000) are
defined as a multiple of a unit governing safe distance $D_{safe}$. The domain for the most favourable weather and sailing condition, i.e., $D_{safe} = 0.5$ n.m., as presented in his paper, is reproduced in Figure 5.2 along with the proposed equivalent domain for the basic case in solid line. Compared to the proposed domain, Smierzchalski significantly overestimates the fore side as well as the port side and starboard side. With Smierzchalski’s domain independent on the vessel size and speed, there is still overestimation even for a larger and faster vessel (LOA = 300m, speed = 25 knots) in the proposed domain as shown in the dotted pink line. It should be noted that Smierzchalski’s estimations of the port and starboard sides lack empirical evidence but was based on hypothesis of the navigational rules. It can be concluded that though the hexagonal domain of Smierzchalski is an improvement over Goodwin’s domain in terms of the shape, it remains an oversimplification.

![Figure 5.2 Comparison with Hexagonal-type Ship Domain](image)

Figure 5.2 Comparison with Hexagonal-type Ship Domain
3) **Comparison with elliptical-type domains based on attributes of single ship**

Figure 5.3 shows the half-elliptical asymmetrical domain proposed by Coldwell (1983) for a head-on encounter of the OS with LOA = 200m, together with the proposed equivalent domain for the base case.

The comparison shows that Coldwell’s domain is reasonably compatible with the proposed domain on the fore side but overestimating the space requirement on the starboard side while underestimating the port side. It should be noted that to account for the general preference of navigators to pass on the port side instead of the starboard side, Coldwell’s domain on the starboard side is assumed larger than that on the port side. Had he not imposed this constraint, his half-elliptical domain would be a good match of the proposed domain, particularly for the higher speed ship (speed = 20knots) since Coldwell’s domain is not dependent on ship speed.

Coldwell (1983) also modeled for an overtaking encounter, resulting in a symmetrically full-elliptical domain as shown in Figure 5.4. This is a closer match to the proposed domain, although, in adopting the symmetrical model, the stern side appears overestimated.
Fujii (1971) also considered the elliptical domain but modeled it around the TS
instead of the OS. This is plotted in Figure 5.5 along with the proposed single equivalent domain. Fujii’s domain matches well with the proposed domain but is smaller on the lateral sides, particularly on the fore side. The resulting comparison is interesting and worth noting. The smaller size of Fujii’s domain on the fore side is resulted from the fact that the size of OS is larger than or equal to the size of TS; and yet the domain of Fujii’s model is only in relation with the size of TS. By letting the LOA of OS be smaller than TS, for example, 150m for OS, the resultant equivalent domain quite matches with Fujii’s domain especially in the fore side shown in Figure 5.5. The result shows that the Fujii’s domain is suitable for the condition when the size of TS is larger than the size of OS; however, the model still cannot take into account the effect of change of speed. More importantly, this confirms the assumption that the attributes of both the OS and TS are important and should be considered in constructing the ship domain.
Summarizing the discussions on the comparisons of the proposed domain with the three shape types of domains from previous works, it may be concluded that the elliptical domain is the closest to the proposed domain. Nevertheless, as the elliptical shape is governed by the radii at the axes, the constraints, such as the symmetry on the elliptical shape tend to underestimate the lateral separation and overestimate the rear separation.

5.2.2 Comparisons with Domains based on Ship Pair

1) Comparison with polygonal-type domains based on attributes of ship pair

Pietrzykowski (2009) developed an octagon domain for a specific pair of moving ships. Therefore for comparison, a pair of moving ships with their attributes are shown in Table 5.2.

<table>
<thead>
<tr>
<th></th>
<th>OS</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOA(m)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Speed(knots)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Heading(degree)</td>
<td>0</td>
<td>180</td>
</tr>
</tbody>
</table>

Using pilot’s input on hypothetical encounters of OS with TS in the opposite direction, the resulting domain is reproduced in Figure 5.6 along with the proposed domain. Clearly the proposed domain is much smaller than Pietrzykowski’s, although the shape appears similar. This is because the Pietrzykowski’s domain is developed for ships sailing in open seas where there are less space constraints and thus the domain tends to be larger.
Pietrzykowski (2009) further extended his model using a more refined 24-sided polygon and introducing a fuzzy function to reflect the level of navigational safety, denoting this by $\gamma \in [0,1]$ where $\gamma = 0$ represents the very safe situation and $\gamma = 1$ represents the very dangerous situation. Taking into account the varying levels of navigational safety, Pietrzykowski’s domain is averaged for the different courses of TS, for the cases $\gamma = 0.7, 0.8$ are reproduced along with the proposed domain in Figure 5.7 (a). The comparison shows that there is very good match for the case $\gamma = 0.8$ particularly in the fore side and the port and starboard sides. This means that our proposed model for restricted waters is compatible with Pietrzykowski’s model when the safety level is lowered. Pietrzykowski’s domain tends to be smaller on the stern side compared to the proposed domain. This may be due to Pietrzykowski’s method of data collection. In seeking the pilot’s input on the hypothetical scenarios, the navigators may be less sensitive to ships located astern, especially when both
ships are travelling at the same speed and hence with little chance of any potential collision.

For the purpose of further comparison, the case of both ships with \( \text{LOA} = 300 \text{m} \) at the speed of 15 knots as shown in Figure 5.7 (b) is examined. There is again good match between the domains, particularly on the fore side, although Pietrzykowski...
predicted a larger increase in the domain on the port and starboard sides.

Pietrzykowski postulated a more rounded domain resulting in the port and starboard sides approaching the length of the fore side. However, based on the literature on ship domains reviewed earlier, most researchers supported a much larger fore side than the port and starboard sides.

Summarizing this, there is generally good compatibility between the proposed domain and Pietrzykowski’s domain, suggesting well that the proposed domain model is suitable.

2) Comparison with elliptical-type domains based on attributes of ship pair

The concept of the Kijima’s domain (2006) is similar to the proposed domain in this research which created the two individual domains for OS and TS in elliptical shape. The resulting Kijima’s domain is reproduced in Figure 5.8 along with the proposed domain. It is clear that the Kijima’s domain overestimates the size of domain along the lateral axis. The Kijima’s analytical model assumes the length of domain on the port and starboard side to be a relationship of the tactical diameter of the ship. The estimation of the tactical diameter is not rigorous because it is based on another much earlier work (Arimura et al., 1994). In addition, the plot of domain in Kijima’s paper (2006) suggests that the lateral dimension is much smaller than the longitudinal dimension. Therefore, this confirms that the lateral domain is overestimated. On the other hand, according to another research, the DCPA for head-on situation is 0.36 n.m. between ships (Bin, 2006). Therefore, the domain proposed in this research is more reasonable because the resultant passing distance
on the side by side is nearly 0.4 n.m. for ships sailing at 15 knots and is closer to recommended passing distance. In addition, along the longitudinal axis, the Kijima’s domain matches the proposed domain on the stern side but overestimates it on the fore side.

![Figure 5.8 Comparison with Elliptical-type Domain based on Attributes of Ship Pair](image)

5.2.3 Summary of Comparisons of Ship Domains

To conclude, based on the comparisons conducted above, it is confirmed that the construction of ship domain should take into account both the attributes of OS and TS in an encounter. The size of ship domain is positively dependent on both the size and speed of the ship. The relative situation between OS and TS is also important because of the difference between encounter types.
The elliptical domain is the closest domain to the proposed polygonal domain. On the other hand, the elliptical curve restricts the domain shape in certain direction; for instance, on the lateral direction without good reason. The domain is probably asymmetrical with respect to the lateral axis. Although there is significantly larger domain on the fore side, the domain area on the stern side should be sufficiently maintained to make sure ships can pass safely. With respect to the longitudinal direction, the domain is almost symmetrical with slightly smaller domain on the port side compared to the starboard side. Given that the proposed domain is variable with ship length and speed, it is more advantageous over most of the existing domains. The domain of the reference ship of 200m long fits most of the domains indicates that the proposed domain with respect to the LOA of ship is quite reasonable. The speed influence on the size of the proposed domain is proved to be correct by comparing it with Fujii’s domain at low speed and with Coldwell’s domain at high speed. The comparison between the proposed domain with Pietrzykowski’s domain validates the capability of the proposed domain in considering ships approaching from all directions.

5.3 INTERPRETATION OF SHIP DOMAIN IN ENCOUNTER

The domain shape and size, discussed in previous section will exert significant influence on the navigational behavior in a close encounter. The summation of the two domains in relation with the relative bearing and heading of the two ships serves as a safety criterion. It will determine the situation at which a collision-avoidance action, either change on ship heading and/or sailing speed is necessary. In this section, the influence of ship domain is examined on the range of heading or speed
when an action is needed. The results will be compared with another common safety criterion, that is DCPA/TCPA. It will be followed by illustrating the use of ship domain in a navigational encounter which improves the modeling of navigational safety. The discussions will be conducted through five case studies.

5.3.1 Understanding Ship Domain in Terms of DCPA/TCPA

DCPA and TCPA are traditional safety criteria defining the distance at the closest point of approach and the time left to the point. As an alternative safety criterion, the ship domain confines the navigational behavior by defining a spatial constraint between ships. This section will explain how the ship domain and the DCPA/TCPA are influencing the navigational options such as heading and sailing speed. Illustrations will be conducted by determining the situation at which a collision-avoidance action is needed. Two case studies will be conducted separately for considering the change of heading and the change of speed. Case 1 will examine the range of heading when an action is needed assuming the ship speed is constant; Case 2 will identify the range of ship speed when an action is needed assuming the ship heading will not change.

The results from both studies will be compared with the results from the safety criterion of DCPA and TCPA. The latter criterion requires the satisfaction of the equation as follows

\[ \text{DCPA} < \text{DCPA}_{\text{lim, } x} \]  

(5.1)

for all the encounters while \( 0 \leq \text{TCPA} < \text{TCPA}_{\text{lim, } x} \). For all the case studies in this
chapter, the time of taking action is assumed at the initial stage; hence the limit of TCPA ($TCPA_{lim,a}$) has no effect on restricting the navigational options. As long as the DCPA exceeds the limit value, an action becomes necessary, and the magnitude of the action is decided by the criterion of $DCPA_{lim,a}$.

Case 1: Heading range where action is necessary

Consider a crossing encounter between two ships denoted by OS and TS, which have navigational attributes shown in the Table 5.3. It is obvious that there exists a heading range between $[\theta_1, \theta_2]$ such that the OS will encroach into the ship domain if no action is taken as illustrated in Figure 5.9. Based on the proposed ship domain model, the limiting ship heading is found to be $\theta_1 = -16.7^\circ$ and $\theta_2 = 5.4^\circ$ for encounter 1 and encounter 2 respectively.

<table>
<thead>
<tr>
<th>Table 5.3 Navigational Information of Ships in a Crossing Encounter</th>
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<tbody>
<tr>
<td><strong>X_0</strong>(n.m.)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td><strong>Y_0</strong>(n.m.)</td>
</tr>
<tr>
<td><strong>LOA</strong>(m)</td>
</tr>
<tr>
<td><strong>Speed</strong>(knots)</td>
</tr>
<tr>
<td><strong>Heading</strong>(degree)</td>
</tr>
</tbody>
</table>

Note: the heading of OS when an action is needed is to be determined.
The difference in the heading range when an action is necessary are compared between the criterion of ship domain and the criterion of DCPA and TCPA in Figure 5.10. Under the condition of \( DCPA_{\text{lim}} = 0.1 \, \text{n.m.} \), the heading range when an action is needed is between [\(-10.6, -1.8\)] (degree) and under the condition of \( DCPA_{\text{lim}} = 0.2 \, \text{n.m.} \), the range is between [\(-12.8, 0.36\)] (degree). It is obvious that both of the heading range under the criterion of DCPA is symmetrical with respect to the condition of \( DCPA = 0 \). By comparison, due to the larger size of domain on the fore side, the OS requires larger degree of heading to prohibit the encroachment of domain when cutting across ahead of the TS. It shows the advantages of the ship domain criterion over the criterion of DCPA and TCPA because the former one could take into account the difference of passing ahead and astern of the other ship. It conforms to the regulation requirements and general navigation practices that passing ahead of the other ship is not recommended due to the higher risk.
Case 2: Speed range where action is necessary

Consider the same crossing encounter where the OS is allowed to vary the speed while keeping a fixed heading as shown in Table 5.4.

<table>
<thead>
<tr>
<th>Table 5.4 Navigational Information of Ships in a Crossing Encounter</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS(n.m.)</td>
</tr>
<tr>
<td>X₀(n.m.)</td>
</tr>
<tr>
<td>LOA(m)</td>
</tr>
<tr>
<td>Speed(knots)</td>
</tr>
</tbody>
</table>

The speed range of OS is illustrated and two critical encounters are identified in Figure 5.11. The speed range of OS when an action is needed is between [9.6, 17.4] knots for the critical encounter 1 and critical encounter 2 respectively.
Figure 5.11 Speed Range of OS in Crossing Encounter under Ship Domain

Figure 5.12 shows the difference of speed range when a change of speed is necessary under the criterion of ship domain and the criterion of DCPA and TCPA. The speed range calculated based on the criterion of DCPA and TCPA is $[11.4, 14.3]$ knots under the criterion of $DCPA_{lim} = 1.0 \text{ n.m.}$ and is $[10.1, 16.0]$ knots under the criterion of $DCPA_{lim} = 2.0 \text{ n.m.}$. With respect to the situation when $DCPA = 0$, the difference between the required speed change between increasing and reducing speed under the criterion of DCPA & TCPA is limited. By contrast, by employing the criterion of ship domain, the OS needs to increase more speeds to pass in front of the TS than the amount needs to be reduced to pass astern of TS. Therefore, the behavior of cutting ahead of other ship is discouraged by the criterion of ship domain, which is also tally with the regulations and navigational practices.
These two case studies illustrate how the proposed model of ship domain is used as the safety criterion in a specific encounter in affecting the range of ship heading and speed. It is also indicated that the ship domain is more advanced than the criterion of DCPA and TCPA because the ship domain can effectively discourage the behavior of passing ahead the other ship. This is compliant with the navigational rules.

5.3.2 Using Ship Domain to Better Model Navigational Safety

The foregoing discussion shows that the DCPA/TCPA criterion cannot fully determine the condition at which action needs to be taken and the ship domain model is able to determine the range of condition in compliance with COLREGs. Further, under the proposed ship domain model, the range of condition is highly variable depending on the ship static and dynamic characteristics. This section will illustrate the influence of ship size, speed and relative heading on the range of
condition where a collision-avoidance action is necessary. Three cases are provided sequentially for these illustrations.

**Case 1: Target ships with various lengths**

The length of ship, denoted by LOA, is a major factor influencing the size of ship domain; as a result, the collision-avoidance behavior, both the ship heading and speed will be variable for ships with different sizes. In this section, a crossing encounter is created involving an OS and target ships of different sizes varying from 100m to 300m as specified in the Table 5.5. The heading range when a change of heading is necessary is used for assessing the effect of ship length.

| Table 5.5 Encounter with Varying Ship Lengths for Target Ship |
|------------------|-----|-----|
|                  | OS  | TS  |
| X(n.m.)          | 0   | 1.5 |
| Y(n.m.)          | 0   | 2   |
| LOA(m)           | 100 | 100~300 |
| Speed(knots)     | 15  | 8   |
| Heading(degree)  | -   | -90 |

The influence of ship size on the heading range when a change of heading is necessary is shown in the Figure 5.13, in which a TS of 100m in (a) and of 300m in (b). As the size of TS increases from 100m to 300m, the heading range also enlarges accordingly from [3.6, 18.6] (degree) to [-6.4, 24.1] (degree).
Chapter Five: Model Interpretation

The effect of ship size on the heading range is further presented in Figure 5.14 by considering target ships of various sizes. As the ship size changes from 100m to
300m, the size of the domain is scaled up and therefore the heading range is also enlarged toward two directions in the x-axis denoting the degree of heading in Figure 5.14.

Case 2: Target ships with various speeds

The ship speed, as another major factor influencing the size of ship domain, is analyzed in the section on its influence to the heading range. The similar encounter as in previous section will be used but the ship of TS is allowed to vary from 6 knots to 16 knots as indicated in Table 5.6. For target ships traveling at various speeds, different ranges of heading when an action is needed will be resulted.

<table>
<thead>
<tr>
<th>Table 5.6 Encounter with Varying Ship Speeds for Target Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>X(n.m.)</td>
</tr>
<tr>
<td>Y(n.m.)</td>
</tr>
<tr>
<td>LOA(m)</td>
</tr>
<tr>
<td>Speed(knots)</td>
</tr>
<tr>
<td>Heading(degree)</td>
</tr>
</tbody>
</table>

![Figure 5.15 Critical Encounters for TS of Different Speeds](image-url)
The TS at the speed of 6 knots and 16 knots are selected for illustration in Figure 5.15. The changes of ship heading range under which an action is needed and critical encounters under different scenarios are shown in the figure.

The variations of prohibited range of OS heading are shown in Figure 5.16 with TS speed varying from 6 knots to 16 knots. As the speed of TS increases, the heading range of OS will be enlarged because of the increasing sizes of domain. The heading range is also moving towards the negative direction on x-axis because the change of speed will affect the moving speed of the TS domain. Figure 5.16 shows that as the speed of TS increases, it is increasingly difficult for OS to pass the TS from the fore side. In addition, compared to the effect of ship size, the influence of ship speed on the heading range is more significant.

![Figure 5.16 Effect of Ship Speed on Heading Range](image)
Case 3: Target ships with various headings

The proposed domain in this research is advanced in considering the relative bearing and ship heading between two ships in an encounter. The effect of relative encounter between ships is illustrated using a specific encounter by only varying the heading of the TS. The navigational information of the proposed encounter is specified in the Table 5.7.

<table>
<thead>
<tr>
<th></th>
<th>OS</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(n.m.)</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Y(n.m.)</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>LOA(m)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Speed(knots)</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Heading(degree)</td>
<td>-</td>
<td>-70~130</td>
</tr>
</tbody>
</table>

Figure 5.17 shows the heading ranges when an action is necessary for OS with respect to different headings of TS varying from $-70^\circ$ (a) to $-130^\circ$ (b). It shows that the varying heading of TS changes the encounter significantly by leading the
OS to pass the TS on the fore or stern side in (a) or to pass TS side by side in (b). Since the fore and stern sides are generally larger than the port and starboard side in the proposed domain, the width of the heading range of OS is slightly reduced from $20.7^\circ$ (a) to $17.5^\circ$ (b).

Figure 5.18 further shows the changes in the heading range of OS with respect to the variations of the heading of TS in $10^\circ$ discretization interval. As the heading of TS changes from $-70^\circ$ to $-130^\circ$, the range of OS heading increases slightly and moves towards the negative direction along the x-axis. It indicates that it becomes more difficult for the OS to pass the TS from the fore side. All the changes suggest the proposed ship domain has been proved to account for the change of relative heading between the two ships in an encounter and the effect is reflected in the heading range of OS in this case study.

![Figure 5.18 Effect of Ship Heading on Heading Range](image_url)
5.4 NAVIGATOR’S PERCEPTION OF DOMAIN

The proposed domain discussed earlier is represented by an envelope around the own ship and target ship. In the proposed model, the summation of the two domains in accordance with the heading of the two ships as well as the relative bearing will determine the proximity, which navigators will keep their ships from each other while navigating in close waters. The resultant single proximity measure represents the behavioural mean for the given fixed condition. While this is a useful form to represent and understand how navigators will interact with each other, it is reasonable to assume that not all navigators will behave in a similar fashion.

In practice, navigators will perceive the needed spatial separation between ships differently for a variety of reasons. Some of these reasons may be attributed to the characteristics of the pilots such as human judgment, navigational experience and willingness to take risks. The prevailing mood and emotional state of the pilot which may be further influenced by such factors as trip purpose or the need to keep to a schedule can also contribute to variation in spatial perception. In other words, for a particular ship encounter under a given navigational condition, the ship domains governing the two ships are likely to be a stochastic rather than a deterministic one. Hence in developing a more realistic model, it would be useful to consider introducing a stochastic element to the proposed model of ship domain. For the purpose of this work, it is assumed that such stochastic behavior is attributed to human perception alone and that this can be observed from the navigational data used in this study.
Following the calibration of the proposed model of ship domain, it is possible to extract the observed difference in the proximity between ships and the calibrated ship domain. This uncertainty is given by $d$ which is the observed space separation between OS and TS. Suppose that the calibrated combined ship domain is given by $SD$, then we can define a non-dimensional ratio $\rho = \frac{d}{SD}$. Using only the data which contribute to the calibration of the model, i.e., the data only represent encounters which are deemed to be in a close encounter situation, the distribution of $\rho$ will represent the variation in the perceived ship domain among the population of navigators. This presupposes that the distribution of spatial perception is proportional to the modeled ship domains, which obviously simplify the perception model. It is further assumed that this variation of perception difference is independent of the encounter type but strictly a characteristic of the navigator-and-ship entity observed. Given this, it is possible to combine all observations of $\rho$ in the calibrated dataset and consider a general perception model for all encounters.

Figure 5.19 (a) and (b) show the cumulative distribution of $\rho$ along with the fitted beta distribution for the daytime and nighttime data respectively. Both sets of data show that there is considerable scatter around the mean.

Figure 5.20 shows the probability density function of the fitted beta distributions in the daytime and nighttime conditions. The distribution for the day is quite symmetrical in nature with a standard deviation of 0.226. On the other hand, the distribution for the night data is somewhat skewed to the left with a standard deviation of 0.24. This implies that there is greater variation in spatial perception under the night condition. Moreover, the skew in the night data also implies that
there is a slight tendency for many navigators to be a little more conservative, though there remains some who perhaps due to poorer in judging distances tend to adopt smaller domain sizes.

Figure 5.19 Cumulative Distribution of $\rho$ and Fitted Function in Day & Night Conditions
Based on the perception model obtained, it is possible to consider a stochastic ship domain plot. This is illustrated using a particular example of ship size of LOA= 100m travelling at a speed of 15 knots. Under this situation, the average ship
domains along with the corresponding $15^{th}$ percentile and $85^{th}$ percentile ship domains are shown in the Figure 5.21 (a) and (b) for the daytime and nighttime conditions respectively. It seems that $85^{th}$ percentile ship domain in the nighttime condition is larger than that in the daytime condition especially in the fore side.

## 5.5 SUMMARY

In this chapter, compared with many existing domains on the shape and size, the proposed ship domain (presented in Chapter 4) is superior to the existing domains in modeling the space separation in relation with the ship size and speed as well as relative bearing and heading. Further, the influences of these factors are presented by creating five case studies. The cases studies prove that the ship domain is better than the DCPA and TCPA as a criterion of safety. It is also demonstrated that by taking into account the above-mentioned factors, the ship domain can model the navigational behavior more correctly which are compliant with navigational rules. The variations in perceiving the ship domain are interpreted as one of the reason contributing to the differences in the behavior from different navigators. It is found that navigators perceive domains differently in the daytime and nighttime due to the different visibility condition; navigators generally tend to be more conservative at night than in the daytime. The identified perceptional errors also show the potentials to be incorporated in the application model.
6.1 INTRODUCTION

In this chapter, the proposed ship domain is applied to planning navigational paths in restricted waters. The problem of path planning for marine navigation is firstly reviewed. Based on the understanding of the problem, the concept of planning paths using Genetic Algorithm (GA) is developed, which is followed by model specifications. The GA-based path-planning model will be further illustrated by two case studies of ships entering or leaving Singapore port. The case studies will be used to examine the influence of ship domain on navigational paths and travel times respectively.

6.2 GA-BASED PATH PLANNING

6.2.1 Path Planning in Restricted Waters

Planning navigational paths in restricted waters are different from long-term path planning from port to port or the short-term planning by directly controlling ship movement in real time. As the middle level of planning, path planning in restricted waters is concerned with the generation of particular stages of the route. A safe manoeuvre, course change and/or speed change, must be initiated by navigators in cases of multiple encountering ships, and the actions should take into account the geometric and geographical constraints, for example, the existence of restricted zone
and narrow channel. Hence the path planning in restricted waters is a discrete process, which must be proactive and occurring at specific points, depending on the on-coming traffic and environment situation.

A typical case of the middle level of path planning occurs to pilots assisting ships entering and leaving port waters. The pilotage decisions depend largely on features of waterways, encountering ships, navigational rules, and even sometimes on the environment. For instance, passing ships should be away from the anchorage or restricted area which can only be entered by ships with designated missions; ships sailing in crossing area and narrow channel should have to obey the rules in accordance with COLREGs when interacting with encountering ships; under certain tidal condition, pilots may also need to re-route ship paths in order to enter the anchorage against the current direction.

Therefore the path planning process in restricted waters is very complicated and multiple objectives have been considered in planning the optimal paths (Smierzchalski, 1999, Ito et al., 1999, Zeng and Ito, 2001, Tam and Bucknall, 2010b, Szlapczynski, 2011, Wang and Chin, 2011, Wang and Chin, 2012). There are safety considerations which require a vessel to keep sufficient space with other surrounding moving vessels as well as with geometric and geographical constraints. There are also economic considerations so that the navigator needs to minimize travel distance and travel time, improve the smoothness of the path, and reduce the cost caused by fuel consumption as well as the possible surcharges on the arrival/departure time schedule. Furthermore, the navigator may also seek to make decisions based on his personal level of comfort. For instance, the alteration of
course is more preferable than the alteration of speed from the navigators’ perspective. In addition, there is often a comfort range of course and speed alteration from the perspective of navigators, who prefer to accept an acceptable minimal and maximal course changes and speed changes.

Hence in seeking an optimal navigational path, it is important to consider the multiple objectives and the dynamic constraints faced by the ship. It is also important to consider the optimal solution from different perspectives of the port operator, the shipper and the navigators as they tend to have different criteria of optimization. Consequently, the problem of path planning in restricted waters could be formulated as a multi-objective optimization problem in mathematical way.

6.2.2 Definition of GA-based Path Planning

This section defines the GA-based path-planning problem in the presence of static and dynamic spatial constraints as well as time constraints with respect to time schedule. The navigational path should be defined in the format that can be used in GA.

In the GA-based path-planning model, each ship is modeled as a rectangular with ship Length Overall (LOA) and breadth. The geometric center of the ship represents the ship position, which will be used as the waypoint in the whole path. A pair of Origin-Destination (OD) is predefined for the movement of each ship. The navigational path connecting each OD consists of several waypoints linked by linear segments with constant ship speeds in each segment. It is assumed that navigational information, such as ship type, speed and heading at the start time are available for
all the ships, which are the basis in the searching the navigational paths.

In addition, several spatial and time constraints in the real marine situation are modeled accordingly. The ship sails in an environment with some natural constraints (for example, land, canals, shallow waters), as well as other constraints resulting from formal regulations (for example, traffic restricted zone, fairways limits, etc). These constraints are often named as non-navigable areas, and artificially modeled as polygons with vertices, consisting of points extracted from the electronic map. Target ships are identified by the concept of ship arena (Davis et al., 1980), which is an area based upon the distance from TS at which a navigator would start to consider actions. The risk of collisions with identified target ships is further assessed by the concept of ship domain. The ship domain, proposed and calibrated in previous research is adopted around each ship depending on the ship length and speed; the relative condition between ships will be considered by the summation of the envelope of ship domain. In addition, a set of arrival time windows at the destination are prescribed for each ship. A penalty function will be introduced to penalize the ships violating the time window constraints.

The environmental condition (the direction and velocity of current and wind) will also be considered in determining the resultant ship speed over ground. The tidal effect is modeled as a time window of the arrival time at the area with restricted water level or the tidal gate. Regulations at narrow fairways and TSS area are specifically modeled by introducing some specialized constraints and objective functions.
Each Navigational Path (NP) connects the origin point $s_i$ and designation point $s_{i+1}$ by introducing several waypoints ($s_i : i = 2, \ldots, I$). All the points are defined by a pair of coordinates $(x, y)_i$, linked by linear segments $i$ ($i = 1, \ldots, I$) with constant ship speeds $v_i$ in each segment. In GA, each NP is represented by a single individual (chromosome). Each individual in the population consists of a fixed number of genes; each of the gene represent a point defined in Equation 6.1, contains the position of the point and the ship speed traversing the following segment starting from the point:

$$gene (s_i) = \{x_i, y_i, v_i\}$$  \hspace{1cm} (6.1)

where $i = 1, \ldots, I$ and the ship speed $v_i$ is the Speed Through Water (STW) without the influence of environmental elements. The origin point $s_i(x_i, y_i)$ and destination point $s_{i+1}(x_{i+1}, y_{i+1})$ are the same for all individuals in the population. By combining all the genes sequentially, the chromosome defines well a navigational path, allowing both course change and speed change at the waypoints.

6.2.3 GA Specifications for Path Planning

6.2.3.1 Generation of initial population

In creating the initial NPs, a solution domain is required for searching purpose. The solution space is a dynamic area free of static navigational constraints, moving ships and their domains. The solution space is defined on a $(x,y)$ dimension at time $t$ (Smierzchalski and Michalewicz, 2000) such that it is given by
\[ SP(t) = O - \bigcup_{m=1}^{M} C_{\text{static}} - \bigcup_{n=1}^{N} SD_n(t) \]  (6.2)

where \( O \) is the observation area, \( C_{\text{static}} (m = 1, \ldots, M) \) represents the set of static navigational constraints governing the non-navigable area, and \( SD_n(t) (n = 1, \ldots, N) \) represents the safety domain of ship \( n \). The speed decision variable \( v_i \) takes a random value selected from a discrete domain of available speed, varying within ‘full speed’, ‘half speed’ and ‘dead slow’, etc. Based on the solution space, a NP is feasible if the position of the ship along the NP at any time \( t \) belongs to the set of solution space \( SP(t) \). NPs which cross the restricted area generated by static and dynamic constraints are unsafe and will be accounted for by a penalty value in the fitness function, which will be discussed in the later section.

The initial population of potential NPs could be generally obtained by randomly creating a number of waypoints and the corresponding segments with the speeds within the solution domain. Although this provides a variety of potential NPs, it may take a long time to obtain such a feasible solution because of the dynamic constraints which vary significantly with time. It is also time-consuming in convergence. Thus, an alternative method is proposed. This involves firstly generating an intuitively correct path based on static constraints and secondly adjusting the path within a tolerable variation. The effect is to create a pseudo random NP that is highly feasible. The intuitively correct path may be obtained by:

- Extracting historical NPs, connecting the start point and the destination point;
• Consulting experienced navigators or pilots for expert judgment on NPs;
• Determining safe paths by other methods.

The individual in the population is one navigational path of waypoints and segments; in the case of optimizing paths for more than one ship simultaneously, each individual is a set of paths for all ships involved. Under this case, a customized type of individual has to be defined if the GA is realized using MATLAB toolbox.

6.2.3.2 Crossover and mutation operators

A set of operators are devised to improve the searching performance for optimal navigational paths. Offsprings are generated by employing the operators to replacing the worst individual in the population. In general, the selection of each operator is performed randomly.

In the crossover operator, two parental NPs are each randomly divided into two parts and recombined by interchanging the first parts to form two new individuals of NP. In general, to increase the genetic diversity, 100% crossover probability seems to be reasonable; thus all offspring is made by crossover. However, this may result in premature performance in the GA especially if the initial population is generated based on expert judgment and intuition. Also the solutions from GA with high value of crossover probability will have less variability in the population, so that the chance of finding the optimal path is reduced. In addition, for a continuous system, the next optimum point can be found quickly on the basis of the present information with a fraction of the better chromosomes. The better probability is confirmed as 80% according to the previous simulation results (Zeng, 2003).
The common mutation operators are mainly based on random selection. However, it may be very time-consuming to reach the convergence or result in no good optimum. Innovative mutation operators have been specially designed to improve the performance of GA (Jing et al., 1997). The adopted operators in this research include:

1) Imposing a large random change waypoint’s coordinates in a path, which can be either feasible or infeasible;

2) Fine-tuning waypoints in a feasible path for shape adjustment on the coordinates of waypoint in a local clearance of the path;

3) Deleting a waypoint from an infeasible path so that the adjacent waypoints are linked by new segment;

4) Exchanging the coordinates of selected adjacent waypoints to eliminate two consecutive sharp turn for either feasible or infeasible path; the probability of selecting the nodes is proportional to the sharpness of the two turns (measured by angles between the path segments) at the two nodes;

5) Smoothing the turns around a waypoint of a feasible path by ‘cutting corners’;

6) Fixing a randomly selecting infeasible segment in a path by ‘pulling’ the segment around its intersecting obstacle;

7) Replacing a speed value for a randomly selected path segment from a predefined finite domain of possible speed.

Although the change of course is often considered as the main collision-avoidance manoeuvre, in some situations where exclusive course change cannot avoid collisions, an additional change of speed might be beneficial. Therefore, the
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mutation of changing speed becomes considerably useful in restricted waters.

6.2.3.3 General specifications of fitness function

Each individual NP in the population should be evaluated based a defined fitness function. In this research, the basic fitness function will encompass the considerations of safety, economic and operational comfort of navigators, as listed in Table 6.1.

<table>
<thead>
<tr>
<th>Optimization criterions</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety considerations</td>
<td>Minimize safety cost by keeping sufficient safe distance to ship domain or static navigational limits</td>
</tr>
<tr>
<td>Economic considerations</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>Minimize the total distance between OD</td>
</tr>
<tr>
<td>Travel time</td>
<td>Minimize the total travel time along the NP</td>
</tr>
<tr>
<td>Smoothness</td>
<td>Minimize the sum of curvature at each waypoint</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Minimize the total fuel consumption along the NP</td>
</tr>
<tr>
<td>Costs related to time schedule</td>
<td>Minimize the cost related to time schedule constraint</td>
</tr>
<tr>
<td>Comfort considerations</td>
<td>Minimize the course changes and speed changes which are beyond the lower bound and upper bound of comfortable changes.</td>
</tr>
</tbody>
</table>

Most of the items in Table 6.1, for instance, economic considerations except the costs incurred due to time window schedule are defined based on the general meaning of objectives, that is, to minimize the travel distance, travel time and fuel cost, and make the path as smooth as possible. For the considerations of safety, costs related to the time schedule, and the comfort of navigators, special approaches are required to handle the general constraints in the GA. This is because GAs are directly applicable only to unconstrained optimization; thus it is necessary to use
some additional methods that keep solutions in the feasible region. The most popular approach in GA community to handle constraints is to use penalty functions that penalize infeasible solutions by reducing their fitness values in proportional to their degrees of constraint violation (Michalewicz et al., 1996). This approach will be adopted in the path-planning model by defining corresponding penalty functions for spatial constraints, time constraints and considerations of navigators’ comfort, which will be specified below.

The fitness function for any navigational path \( p \), comprising the components of safety, economy and comfort is formulated as

\[
\text{Fitness} \ (p) = w_s \cdot \text{Safety} \ (p) + w_e \cdot \text{Economy} \ (p) + w_c \cdot \text{Comfort} \ (p)
\]  

(6.3)

where \( w_s, w_e, w_c \) are weight coefficients for the different criterion components which will be specified below sequentially.

As mentioned above, the violations of ship domains and stationary constraints are penalized by a safety cost in the formulation of the safety criterion. The safety criterion, denoted by \( \text{Safety} \ (p) \) measures the sum of the maximum safety costs in each segment of a path \( p \), given by

\[
\text{Safety} \ (p) = \sum_{i=1}^{I} \max_{r=1}^{M+S} \left( sc_{rij} \right)
\]  

(6.4)

In equation (6.4), \( sc_{rij} \) represents the safety cost for each segment \( i \) with respect to spatial constraint \( j \) which is either general stationary constraints \( m \) or another ship
\[ sc_j = G_c \cdot e^{-(d_j - \xi_j)} \]  

(6.5)

in which \( d_j \) is the smallest distance along segment \( i \) to constraint \( j \); \( \xi_j \) is the "safe" distance between the ship in segment \( i \) to constraint \( j \); if the constraint \( j \) is stationery, \( \xi_j \) is determined by the domain of ship in segment \( i \); if the constraint \( j \) is a dynamic ship, \( \xi_j \) is the summation of domains of the ship in segment \( i \) and ship \( j \) along the relative bearing direction; \( G_c \) is the safety cost of a collision which may be different for collision with static constraint \( m \) and collision with another ship \( n \); \( \omega \) is a coefficient parameter of the exponential penalty function, which is the same as Equation (4.4) in Chapter 4.

The economy criteria in the fitness function comprises following components: total travel distance \( \text{Dist} \ (p) \), travel time \( \text{Time} \ (p) \), path smoothness \( \text{Smooth} \ (p) \), fuel consumption \( \text{Fuel} \ (p) \) and penalty cost of non-schedule adherence \( p_n \ (p) \), i.e.,

\[
\text{Economy} \ (p) = w_d \cdot \text{Dist} \ (p) + w_t \cdot \text{Time} \ (p) + w_m \cdot \text{Smooth} \ (p) + w_f \cdot \text{Fuel} \ (p) + w_p \cdot p_n \ (p)
\]  

(6.6)

where \( w_d \), \( w_t \), \( w_m \), \( w_f \), \( w_p \) are the weight coefficients for distance, travel time, path smoothness, fuel consumption and penalty to time schedule respectively.

\( \text{Dist} \ (p) \) is the total distance between the origin and the destination points of the path.
given summing up each segment length $i_i$

$$\text{Dist} (p) = \sum_i i_i$$  \hspace{1cm} (6.7)

$\text{Time} (p)$ is the total travel time along the path by summing up the times spent in each segment

$$\text{Time} (p) = \sum_{i=1}^i t_i$$  \hspace{1cm} (6.8)

where $t_i$ denotes the travel time during the segment $i$.

The smoothness of a path $\text{Smooth} (p)$ is the sum of the "curvature" $\kappa$ at each node point $s_j$, i.e.,

$$\text{Smooth} (p) = \sum_{i=2}^i \kappa(s_j)$$  \hspace{1cm} (6.9)

where the “curvature” is a measure of the absolute angular course change $\Delta \theta_{i,i+1} \in [0, \pi]$ from segment $i$ to $i+1$,

$$\kappa(s_{i+1}) = \frac{\Delta \theta_{i,i+1}}{\min {l_i, l_{i+1}}} \hspace{1cm} i = 1, \ldots, I - 1$$  \hspace{1cm} (6.10)

The rate of fuel consumption is strongly dependent on speed (Ronen, 1982), so that the fuel consumed in the entire path $\text{Fuel} (p)$ is defined as
\[ \text{Fuel} (p) = \sum_{i=1}^{I} f(v_i^2 t_i) \]  

(6.11)

where \( f(\cdot) \) is a function of evaluating fuel consumptions, and \( v_i (v_a \leq v \leq v_d) \) the speed during segment \( i \), subject to a minimum and a maximum cruising speed which define the range of ship speeds. \( v_a \) is the minimum steerage speed and \( v_d \) is the vessel service speed, also known as design or cruising speed.

The penalty function considering time schedule \( p_a (p) \) could penalize the non-schedule adherence, such as early and late arrivals. Within a specified time window, no penalty cost is involved; beyond the time window, a basic linear cost function is employed as

\[
p_a (p) = \begin{cases} 
0 & \text{if } T_i \leq AT (p) \leq T_u \\
\beta_i (T_i - AT (p)) & \text{if } AT (p) < T_i \\
\beta_z (AT (p) - T_u) & \text{if } AT (p) > T_u 
\end{cases} \]  

(6.12)

where \( AT (p) \) is ship arrival time along path \( p \) as

\[ AT (p) = t_o + \text{Time} (p) \]  

(6.13)

where \( t_o \) is the current clock time, \( T_i \) and \( T_u \) are the lower and upper limit of tolerance in arrival time, and \( \beta_i \) and \( \beta_z \) are cost-rates.

According to Rule 8b in COLREGs (COLREGs, 1972), actions taken to avoid
collision should be positive and obvious. This requires the course alteration values to be great enough to make the manoeuvre apparently to another vessel observing visually or radar. On the other hand, too many significant changes in course and speed are not preferable because pilots will need much effort to recover the changes. Therefore minimum and maximum acceptable changes of course and speed are defined together with a criterion which is a function of pilots’ comfort during operation. Comfort \( p \) is defined as a measure of the penalty of course changes and speed changes in the path, i.e.,

\[
\text{Comfort} \quad (p) = \sum_{i=2}^{I} P_c(s_i) + \sum_{i=2}^{I} P_v(s_i)
\]  

(6.14)

where \( P_c(s_i) \) is the penalty cost of course changes at node \( s_i \), and \( P_v(s_i) \) is the penalty cost of speed changes at node \( s_i \), which are linearly defined respectively as,

\[
P_c(s_i) = \begin{cases} 
0 & \Delta \theta_{\min} \leq \Delta \theta_{i,j+1} \leq \Delta \theta_{\max} \quad \text{or} \quad \Delta \theta_{i,j+1} = 0 \\
\delta_1 (\Delta \theta_{i,j+1} - \Delta \theta_{\min}) & 0 < \Delta \theta_{i,j+1} < \Delta \theta_{\min} \\
\delta_2 (\Delta \theta_{i,j+1} - \Delta \theta_{\max}) & \Delta \theta_{i,j+1} > \Delta \theta_{\max}
\end{cases}
\]  

(6.15)

\[
P_v(s_i) = \begin{cases} 
0 & \Delta v_{\min} \leq \Delta v_{i,j+1} \leq \Delta v_{\max} \quad \text{or} \quad \Delta v_{i,j+1} = 0 \\
\delta_3 (\Delta v_{i,j+1} - \Delta v_{\min}) & 0 < \Delta v_{i,j+1} < \Delta v_{\min} \\
\delta_4 (\Delta v_{i,j+1} - \Delta v_{\max}) & \Delta \theta_{i,j+1} > \Delta \theta_{\max}
\end{cases}
\]  

(6.16)

In Equations (6.15) and (6.16), \( \Delta \theta_{i,j+1} \) and \( \Delta v_{i,j+1} \) are course changes and speed changes at node \( s_i \), respectively; \( \Delta \theta_{\min} \) and \( \Delta \theta_{\max} \) are the lower and upper limits of comfortable course change; \( \Delta v_{\min} \) and \( \Delta v_{\max} \) are lower and upper limits of
comfortable speed changes, and $\delta_1$, $\delta_2$, $\delta_3$, $\delta_4$ are coefficient parameters. Since the preference of taking course change and speed change are different, coefficient parameters are also set differently.

### 6.2.3.4 Fitness function account for localized effect

Besides the considerations of safety, economy and operational comfort, the navigational paths are also affected by regulation rules such as the requirements of sailing in areas under Traffic Separation Scheme (TSS). In addition, the navigational paths could be different under the presence of environmental fields, such as wind, current flow and tide. It is particularly important when the weather condition is adverse for sailing, for example, the wind goes against the expected sailing direction or the tidal current is not suitable for entering the anchorage. By considering the effect of these environmental factors, the prediction of the navigational paths can be more accurate and reliable.

Since these components of regulations and environmental condition are not the major contributions of this research, details on the derivation of fitness function considering the influences of these elements are placed in Appendix B and Appendix C respectively.

### 6.3 ILLUSTRATIONS OF SHIP DOMAIN IN PATH PLANNING

The application of ship domain in planning optimal paths will be illustrated in this section using case studies involving several ships entering, leaving and passing
Singapore port waters. Two case studies are conducted to examine the influence of ship domain on navigational paths and the influence of ship domain travel time respectively.

6.3.1 Case Study 1: Influence of Ship Domain on Navigational Paths

To illustrate the influence of ship domain in planning navigational paths, a case study involving several ships arriving at, leaving, or passing the Singapore Straits and the Singapore port has been undertaken. The study area measures 9.3 n.m. × 6.6 n.m. (plotted in thick line in Figure 6.1) and has a variety of navigational constraints such as land limits, fairway limits and restricted areas for anchorages.

Figure 6.1: Background of Study Area in the South of Singapore Port
Four ships with their origin and destination points are involved in this case study. In order to illustrate the influence of ship domain which is variable with ship size and speed, two scenarios are created for comparison. The two scenarios are only different in the ship type, size and speed for Ship 2 and Ship 3. The ship attributes and their navigational information for the two scenarios are listed in Tables 6.2 and 6.3 and the differences between the two scenarios are highlighted in bold.

For both of the two scenarios, Ship 1 is a passenger ship coming from west and approaching the Singapore Cruise Center. Ship 2 intends to travel from west and heads for eastern anchorage. In Scenario 1 Ship 2 is a tanker of 205 m at a speed of 11 knots compared to a Very Large Crude Carrier (VLCC) of 407 m for Ship 2 in Scenario 2 traveling at a speed of 20 knots. Ship 3 in both scenarios is a container ship, leaving from Tanjong Pagar terminal and heading east. Ship 3 is in 195 m at 12 knots in Scenario 1 and in Scenario 2 the LOA is 397.7 m and the initial speed is 20 knots.
knots. Ship 4 is the same for the two scenarios as a Bulk Cargo ship, leaving from Pasir Panjang Terminal, and heading south to depart Singapore port waters of the ship’s surroundings. An arrival time schedule ([20, 35], unit: minute) and penalty cost function have been prescribed for Ship 1 in both two scenarios.

Figure 6.2 presents the computed optimal navigational paths with critical encounters in scenario 1. By tracking the navigational path of Ship 1, three critical encounters with respect to the rest of ships are identified. Initially, Ship 1 is involved in an overtaking encounter together with Ship 3. Since Ship 1 has a much higher speed and bigger size over Ship 2 and Ship 1 is under time window constraint, Ship 1 decides to overtake Ship 2 with a safe separation governed by the ship domains of both Ship 1 and Ship 2. Secondly, Ship 1 then encounters Ship 3 in the crossing area. Because of the faster speed and bigger ship size, Ship 1 does not give way to Ship 3 with smaller size and slower speed; thus Ship 1 cuts across safely from the bow of Ship 3 and meets the requirements of ship domain. After turning into Jong Fairway, Ship 1 comes across Ship 4 in head-on encounter; both of the ships pass each other port by port and keep near to the fairway limits on their starboard side in accordance with COLREGs. The overlap of the ship domain is a compromising result of the high speed of Ship 1 who is under time window constraint; if the constraint is violated, high value of penalty cost may be imposed. Finally, Ship 1 reaches its destination within the prescribed arrival time schedule.
Figure 6.2: Optimal Navigational Paths and Critical Encounters for Scenario 1

Figure 6.3: Optimal Navigational Paths and Critical Encounters for Scenario 2
By contrast, the navigational paths and critical encounters for Scenario 2 are presented in Figure 6.3. Due to the increase in the ship size and speed for both Ship 2 and Ship 3, Ship 1 has slackened her speed and give way to both of the other two ships. As a result, instead of overtaking Ship 2, Ship 1 is overtaken by Ship 2 in Scenario 2. The Ship 1 further passes Ship 3 astern and then meets Ship 4 in the crossing area instead of Jong Fairway. The Ship 1 also gives way to Ship 4 to let the ship leaving the fairway before itself entering the port waters. Finally, Ship 1 has to recover its speed to maximum of 20 knots in the rest of the journey in order to avoid the possible penalty due to time schedule.

This illustration demonstrates how the optimal paths of the ships can be simultaneously achieved while satisfying all the COLREGs requirements as well as geometric constraints. More importantly, the comparison of different navigational paths between Scenario 1 and Scenario 2 shows that the ship domain plays a significantly important role in planning navigational paths. It is also illustrated how the navigational behavior, for example, give-way or stand-on of encounters, speed-up or slow-down of speeds are affected by the ship domain. In addition, as a safety criterion, the model of ship domain is proved to provide reasonable navigational paths for all encounter types, such as head-on, overtaking/overtaken and crossing encounters in this illustration.

6.3.2 Case Study 2: Influence of Ship Domain on Travel Time

The previous section has demonstrated in a specific case that how ship domains affect navigational paths, consisting of course change and/or speed change at the waypoints. The changes in course and speed will definitely influence the travel
times to destinations for each ship. Therefore, in this section the travel time is employed to evaluate the influence of ship domain on path planning.

To examine the influence of ship domain on travel time, three scenarios are created. Scenario 1 represents a free-flow condition, which assumes only one ship at a time sailing within the port (see Figure 6.1) under static navigational constraints. Five study ships were selected in turn to assume the free-flow scenario. Scenario 2 represents a normal traffic condition in which all 5 ships moves through the port waters simultaneously subject to the navigational path constraints described in Section 6.2. Scenario 3 is a dense traffic environment involving simultaneous movements of the 5 study ships and another 4 other ships moving within the studied port area. The description of the 5 study ships and the other 4 subsequent ships are shown in Table 6.4. For the purpose of the discussion, only the travel times of the 5 study ships are compared.

Table 6.4 shows the description of the 5 study ships and the other 4 ships in Scenario 3. The intended navigational paths of the 5 study ships and the other 4 ships are shown in Figure 6.4 and Figure 6.5 respectively. Ship 1 is a passenger ship, coming from the west and aiming to enter the Singapore cruise center. The path goes through Strait waters under TSS, Jong Fairway and West Keppel Fairway. Ship 2 is a VLCC passing the port waters in the study area and sails all the time within the TSS areas from east to west. Ship 3 is a tanker leaving the port waters from Jong Fairway and heading towards the east. As a bulk cargo ship, Ship 4 enters the study area from the east and will reach its destination which is Pasir Panjjang Terminal in the north through Jong Fairway and West Keppel Fairway. Ship 5 leaves from the
Tanjong Pagar Terminal on the east and will travel through Southern Fairway, Jong Fairway and West Keppel Fairway until to the west of the study area. Ship 6 is a container ship sailing in the TSS areas from west to east. Ship 7 is a bulk carrier leaving slowly from Western Anchorage and heading east through Jong Fairway and Southern Fairway. Ship 8 travels from west through West Keppel Fairway to enter Pasir Panjang Terminal. Ship 9 sails slowly from the north of the port to West Anchorage by crossing West Keppel Fairway and sailing through Jong Fairway.

Table 6.4: Navigational Information of Ships in Case Study 2

<table>
<thead>
<tr>
<th>SHIP INDEX</th>
<th>SHIP TYPE</th>
<th>LOA (m)</th>
<th>INITIAL SPEED (knots)</th>
<th>ORIGIN POINT (x, y) (n.m.)</th>
<th>DESTINATION POINT (x, y) (n.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Passenger</td>
<td>269</td>
<td>20</td>
<td>(3.500, -0.500)</td>
<td>(5.792, 6.087)</td>
</tr>
<tr>
<td>2</td>
<td>VLCC</td>
<td>398</td>
<td>20</td>
<td>(9.600, 3.700)</td>
<td>(1.500, -0.500)</td>
</tr>
<tr>
<td>3</td>
<td>Tanker</td>
<td>295</td>
<td>15</td>
<td>(2.840, 5.130)</td>
<td>(10.000, 2.800)</td>
</tr>
<tr>
<td>4</td>
<td>Bulk Carrier</td>
<td>205</td>
<td>15</td>
<td>(10.000, 3.900)</td>
<td>(1.500, 7.200)</td>
</tr>
<tr>
<td>5</td>
<td>Tanker</td>
<td>149</td>
<td>15</td>
<td>(7.742, 6.129)</td>
<td>(-0.509, 5.311)</td>
</tr>
<tr>
<td>6</td>
<td>Container</td>
<td>385</td>
<td>20</td>
<td>(3.250, 0.015)</td>
<td>(10.010, 3.350)</td>
</tr>
<tr>
<td>7</td>
<td>Bulk Carrier</td>
<td>142</td>
<td>5</td>
<td>(4.919, 5.474)</td>
<td>(9.985, 4.500)</td>
</tr>
<tr>
<td>8</td>
<td>Tanker</td>
<td>346</td>
<td>7</td>
<td>(-1.510, 4.025)</td>
<td>(3.283, 6.395)</td>
</tr>
<tr>
<td>9</td>
<td>Bulk Carrier</td>
<td>209</td>
<td>8</td>
<td>(0.005, 8.210)</td>
<td>(4.731, 4.653)</td>
</tr>
</tbody>
</table>

Note: Ship 1 to Ship 5 are the study ships and Ship 6 to Ship 9 only appear in Scenario 3.
Figure 6.4: Navigational Paths of Five Study Ships under Free-flow Scenario

Figure 6.5: Navigational Paths of Ship 6 to Ship 9 in Scenario 3
Chapter Six: Model Application

The travel times of the 5 study ships undergoing the 3 different scenarios are compared in the Table 6.5.

<table>
<thead>
<tr>
<th>Ship Index</th>
<th>Travel Time (min)</th>
<th>Changes of Travel Time (min)</th>
<th>Percentage Changes of Travel Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1 Free-flow</td>
<td>Scenario 2 Normal</td>
<td>Scenario 3 Dense traffic</td>
</tr>
<tr>
<td>Ship 1</td>
<td>27.8</td>
<td>34.0</td>
<td>39.0</td>
</tr>
<tr>
<td>Ship 2</td>
<td>23.4</td>
<td>29.0</td>
<td>31.5</td>
</tr>
<tr>
<td>Ship 3</td>
<td>32.9</td>
<td>44.0</td>
<td>53.0</td>
</tr>
<tr>
<td>Ship 4</td>
<td>28.3</td>
<td>51.8</td>
<td>87.4</td>
</tr>
<tr>
<td>Ship 5</td>
<td>35.5</td>
<td>59.3</td>
<td>108.2</td>
</tr>
</tbody>
</table>

As expected, the travel times shown in Table 6.5 are longer with increased traffic density within the port. From the point of view of ship domains, the increased density meant that ships are subject to more physical constraints navigating through the port. The effect of longer travel times also result in lower travel speeds which in turn causes the ship domains to reduce in size thereby allowing a more feasible passage of the vessels through the port. However the changes in travel times in the different scenarios may not be just a simple process of reduction of ship domains. Not only is the size of ship domain are affected by ship size and speed, the rate of change in size of the ship domain is also affected by the ship size, the speed function as well as the bearing of the ship during the encounter. The latter is a dynamic component since any delay in any ship may result in a different condition of encounter. Furthermore, other geometric and time constraints imposed on the navigation will also play a role as they will influence the navigational paths. The following is a discussion to examine the influence of all factors on travel times.
based on the scenarios simulated.

Figure 6.6 shows the changes in travel times of the 5 study ships. Clearly the changes are not uniform between ships as well as between scenarios. The travel times in Scenario 1 as the free-flow condition, are generally influenced by the origin and destination and hence the distance of travel as well as the speed adopted by the ship within the port. Therefore, Ship 2 as a VLCC sailing at higher speed only along the separation zone requires a short travel time.

The travel times of all five ships in Scenario 2 as in the condition of normal traffic density increase compared to Scenario 1 due to interactions between ships. The interactions between Ship 1, Ship 2, Ship 3 and Ship 4 occur at the traffic crossing area outside the Jong Fairway and Ship 5 meets up with Ship 1, Ship 3 and Ship 4 at the junction between Jong Fairway and Southern Fairway. The results in Figure 6.6 show that Ship 4 and Ship 5 are affected more in the travel times compared to
the rest three ships. The possible reasons are identified as follows.

Fundamentally, the influence of travel times is directly related to the chance of exposure to other traffic. It depends on the characteristics of the waterways through which the ships sail and the length of the paths in the waterways. From Figure 6.6, clearly Ship 2 is the least affected in the travel time in Scenario 2 and Scenario 3 whereas Ship 5 is the most affected ship. It is partly due to the fact that the whole path of Ship 2 falls in the TSS areas where ships are not obstructed by traffic from opposite direction; by comparison, the path of Ship 5 covers four different fairways and two junctions including the “T” junction between Southern Fairway and Jong Fairway, and the crossing junction between Jong Fairway and West Keppel Fairway. In the former “T” junction, Ship 5 probably has to give way to Ship 1 which is under time window constraints and negotiate with Ship 4 which is in the same sailing direction. Particularly in Scenario 3, Ship 5 needs to interact with Ship 8 from in the latter crossing junction. In addition, sailing in the Jong Fairway, Ship 5 will meet Ship 7 and Ship 9 in a head-on encounter and hence has to change her course to give way to both of the two ships. Therefore, because of more exposure to other traffic in the fairway and in the junction, Ship 5 is more likely to be delayed in comparison with Ship 2 sailing in the TSS areas which is rarely obstructed by other vessels.

For Ship 1 and Ship 3, the changes of travel times (6.3 min and 11.1 min) in Scenario 2 are less than that of Ship 5 (23.8 min) but more than that of Ship 2 (5.7 min). This can be explained by the fact that only a portion of paths of Ship 1 and Ship 3 fall in the fairway whereas the rest of paths fall in the TSS areas. Therefore
the influence of the type of waterways on travel times for Ship 1 and Ship 3 is limited compared to Ship 5.

Moreover, as shown in Table 6.4, the changes and percentage changes of travel time of Ship 3 are consistently less than those of Ship 4. This can be partially explained by the travel direction with respect to the port waters. Ship 4 plans to enter the port waters using Jong Fairway while Ship 3 is already sailing in the same fairway and is going to leave the port. In deciding the usage of Jong Fairway for ships leaving or entering port waters, the outbound traffic such as Ship 3, is likely to be given the priority to clear her way from the fairway compared to the inbound traffic, for example, Ship 4. It is also related to the speed of Ship 3 (15 knots) which is fast enough to get away from the fairway quickly. Therefore, the faster outbound traffic is more likely to be given the right of way when interacting with inbound traffic which probably has to give way. However, examining another inbound traffic, Ship 1 tends to be not much affected in the travel times as seen Table 6.4. This is because Ship 1 is under a time window constraint which makes Ship 1 more prioritized than other ships, and even Ship 3 must give way to Ship 1.

Besides the previous reasons, the ship LOA also plays a part in affecting the travel times. By examining the size of the five study ships, it has been found that Ship 1, Ship 2 and Ship 3 are generally larger than Ship 4 and Ship 5. This may also contribute to the result that the percentage changes of the travel times for the former three ships (22.6%, 24.2% and 33.8%) are much less than those of Ship 4 and Ship 5 (83.0% and 66.9%) from Scenario 1 to Scenario 2. The reason that the bigger ship is less likely to be affected in the travel time may be due to the
proportional relation of ship domain with ship LOA whereas the relationship between the ship domain with speed is nonlinear. Therefore, as ship speed drops from full speed and half speed, the domain of ship at half speed is more than half of the domain of ship traveling at full speed. To scale down the ship domain to maintain space separation between ships, the ship speed must be reduced significantly. However, due to the proportional relationship between the ship domain and ship LOA, the domain of bigger ship will still be quite large compared to that of smaller ship. Worse still, the reduced ship speed for bigger ship means it has to spend more time in restricted waters and therefore occupy the space for longer time. This makes the navigation between ships in restricted waters even difficult. Therefore, the reduction of speed for bigger ship is less effective than that for smaller ship. Consequently, it is reasonable to conclude that the size of ship is also a contributing factor in deciding which ship should reduce the speed and hence influence the travel time.

Last but not least, by adding four more ships to Scenario 2, the travel times of Ship 4 and Ship 5 increase significantly in Scenario 3 compared with the other three study ships. This is because three of the four add-in ships, Ship 7, Ship 8 and Ship 9 probably encounter Ship 4 and Ship 5 either in Jong Fairway or West Keppel Fairway, whereas Ship 1, Ship 2 and Ship 3 are less likely to be affected. The encountering situations require the Ship 4 and Ship 5 to slacken their speeds even more to achieve optimal paths. Moreover, as seen in Figure 6.6, the increase in travel time from Scenario 1 to Scenario 3 are not likely to be linear with the increase of the traffic density in terms of the amount of ships within the study area. This can be explained by considering three elements. Fundamentally, the proposed
ship domain is not a circular area and it is proportionally related to the size of ship. Therefore, simply treating each ship identically when the traffic density is assessed may not be proper. Secondly, the travel time is highly related to the travel speed. Ship 7, Ship 8 and Ship 9 included in Scenario 3 are generally traveling at lower speeds. Although the limited speed makes the domain smaller, it also prolongs the travel times of these three ships in the fairway. Therefore, these three ships are more likely to interact with the study ships. Consequently, the travel times of Ship 4 and Ship 5 increase significantly because of the need to give way to these three ships. Thirdly, the domain changes dynamically with ship encounters and the process of path planning is also dynamic. Therefore, any slight change in the navigational paths and travel speeds may result in significantly different encounters or even completely eliminate the possibility of involving in an encounter. Therefore this dynamic effect cannot be explained by a simple linear relationship.

To sum up, by analyzing the ship travel times from the simulation of three scenarios of different traffic density, contributing factors to travel times have been identified as the ship length, type of waterways and traffic direction. More importantly, it is identified that the increased travel time is not linearly related to the increased traffic density because of the dynamic effect due to ship domain as well as the process of path planning. Therefore only by combining the dynamic model of ship domain and the path-planning model, the navigational safety in restricted waters can be rigorously modeled.
6.4 SUMMARY

This chapter applies the developed ship domain model for planning optimal navigational paths in Singapore port waters. Based on the characteristics of the proposed domain model, the GA-based algorithm of seeking optimal paths was used. The illustrations of the application of ship domain include two case studies. The first case study addresses the influence of ship domain in affecting the navigational paths. Comparison of scenarios with ships of different sizes and speeds suggests that the adoption of the ship domain in planning paths is effective in modeling the changes of navigational behavior. In the second study, the influence of ship domain on travel time is presented by employing three scenarios with increasing traffic density. Comparisons show that the ship travel time is affected by the ship size and speed, the type of waterways where ships are sailing and the travel direction as either entering or leaving port waters. More importantly, comparing scenarios with increased traffic density, the travel times of ships display nonlinear increase with the amount of additional traffic. This shows that traffic modeling in restricted waters is not only related to the traffic density but also affected by the size and travel speed of ships and the dynamic traffic encounters to be faced with. This dynamic effect can only be solved by incorporating the dynamic ship domain model in the process of path planning.
7.1 CONCLUSIONS AND RESEARCH CONTRIBUTIONS

7.1.1 Conclusions

This research has developed a dynamic and stochastic model of ship domain that can be applied for path planning in restricted waters. The model has been empirically calibrated using traffic movement data within Singapore port waters for both daytime and nighttime. The key findings resulting from this work are summarized as follows.

1) A more definitive domain shape

Previous literature has shown that the ship domain may have a variety of shapes but there is little empirical support for any of them, although some, for example, the circular domain, are less justifiable. This study shows that the domain is unsymmetrical in the fore and stern sides and almost similar between the port and starboard sides. Using empirical data, the study shows that even an unsymmetrical ellipse may not give a sufficiently accurate picture of the domain shape. As the study indicates, it may be best to allow a higher degree of freedom to use a polygonal domain.
2) **A interactive and relatively dynamic domain**

The developed model presents an interactive and relatively dynamic domain around ships. Previous dynamic domains (Pietrzykowski, 2009) have been criticized for hindering assessment of the navigational situation. Different from averaging the dynamic domains to obtain a single domain, this research developed a basic stationary domain around individual ship but a summation of the two domains around ships when used in an encounter. This is more superior because this concept takes into account the relative bearing and heading difference between the ships; which previous models are unable to account for. By using a basic stationary individual domain, the dynamically adaptable domain can be scaled appropriately according to the changing ship speed. Furthermore, by allowing the dynamically changing domains in an encounter, the interactions between ships throughout the navigational movement may be modeled.

3) **A Stochastic Domain Including Human Factors**

The component of human element is often ignored or crudely considered in previous behavioral studies on ship domain. This study represents the first attempt to model ship domain that takes into account variation in human perception among navigators. By introducing a non-dimensional stochastic element in the ship domain model, a distribution of spatial separation as perceived by navigators has been empirically derived. This enables the ship domain to vary between the most conservative to the most aggressive navigators. This should pave the way for further work on a more comprehensive behavioral ship domain model.
4) **Nighttime Domain Distinguished from Daytime Domain**

Hitherto ship domains are assumed similarly applicable for both day and night conditions, perhaps due to lack of study for nighttime conditions. The study shows that this is not true. The ship domain in the nighttime is found to be larger than the one during the daytime. Moreover, the nighttime domain is more sensitive to changes in sailing speed than the daytime domain. More importantly, there is greater variation in perception among navigators at night than in the day along with slight tendency for many navigators to be a little more conservative in the nighttime than in the daytime.

5) **Potential of Iterative Process in Calibrating Ship Domains**

Many previous models of ship domain lack empirical evidence or at best is calibrated only by hypothetical scenarios (Pietrzykowski and Uriasz, 2009). In particular, many calibration methods in previous studies (Fujii and Tanaka, 1971, Goodwin, 1975) suffer a major limitation by relying on traffic density which treats all surrounding ships equally regardless of ship characteristics and proximity. In reality, only the ships in close encounters should be used in the calibration. An iterative approach for calibration is therefore necessary, as the set of data needed for the calibration is not known a priori. This study demonstrates that by adopting an iterative approach to calibration, a converged solution is achievable, even with a dataset that is not prescribed. Allowing this additional degree of freedom gives not only credibility but also confidence in the results obtained.
6) Combined Ship Domain and Path Planning in Modeling Navigational Safety

Previous studies involving ship domain focused only on solving collision-avoidance problem in a close range (Kwik, 1989). On the other hand, those studies on path planning only utilizes a much simplified ship domain model and in a simplified context (Smierzchalski, 1999). This study allows a calibrated ship domain model to be applied in ship path finding interactively. The case studies of navigation within the Singapore port waters well demonstrate that the dynamic and interactive effect of applying the ship domains on multiple moving ships have an impact on the travel path and time of vessels.

7.1.2 Contributions

This research has developed a comprehensive model of ship domain to be applied in planning navigational paths. This research has advanced the understanding of spatial separation in restricted waters by investigating the concept and application of ship domain. Specifically the contributions of this research are as follows:

1) A clearer exposition of the concept, representation and measurement of ship domain based on empirical evidence is made. The work will put to rest the inadequacies of circular and symmetric ship domains and underscore that the representation of ship domains is not as simple as previously assumed. The study adequately factor in ship size and ship speeds in modeling the ship domain.
2) This study has also introduced several components in the ship domain model that hitherto have not been considered. In particular, a behavioral element to account for the variations in perception among navigators has given greater realism to the modeling of ship domain. Furthermore, the introduction of the nighttime effect as distinguished from the daytime condition has resulted in a more superior ship domain for nighttime application.

3) The research extends previous works of ship domain based on a pair of ships in a hypothetical encounter. It demonstrates that by combining the ship domain model together with a path-finding model, the interactive and dynamic effect of ship domains is now possible for multiple ship encounters as well as continuous encounters. This is a significant contribution since previous work has only examined encounters at single points in time and with a fixed pair of vessels but the current work has allowed encounters among multiple ships to be tracked over the entire navigational route. The two features, i.e., interactive and dynamic aspects of safe navigation is a major step forward in modeling navigation, which will be particularly important if done within restricted waters and dense traffic condition.

7.2 POTENTIAL FOR FUTURE RESEARCH

For modeling navigational safety in restricted waters, a comprehensive model of ship domain has been developed and applied in planning optimal paths, taking into account human variations. While the model has been developed with a high degree of scientific rigor, the limitation of data as well as available time resources meant
that there are several areas, which can still be further investigated. In particular, two
aspects can be expanded, i.e., 1) a more comprehensive model to represent human
perception; 2) a model calibration based on multi-ship encounters. The two
directions of potential research are discussed below.

(a) Currently the variation of human perception is uniformly applied for lack of
data. To take into the additional degree of freedom in the model should this
be assumed to vary, for example, between sectors or for different vessel
types. To accomplish this, a modified version of the model will need to be
formulated and calibrated with a larger database.

(b) The current calibration process is based on encounters between vessel pair
although the application is for multiple ship encounters. Ideally, the
calibration can be achieved based on multiple ship encounters. However, this
will require a larger data set to ensure the calibration can be achieved with a
sufficiently high degree of reliability. It will also necessitate a different
formulation of the model and potentially a different calibration procedure.


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WANG YUE YING

1. EDUCATION

2003-2008 B.Eng in Civil Engineering, Dalian University of Technology.
2008-2012 PhD research student, Dept. Civil & Environmental Engineering, National University of Singapore.

2. LIST OF PUBLICATIONS


Appendices

APPENDICES

Appendix A. Genetic Algorithm

This appendix presents the Genetic Algorithm (GA) as the optimization technique employed in this research.

Genetic algorithm is one of the typical heuristic techniques for optimization. As an appealing tool to solve optimization problems, GA is a stochastic optimization algorithm based on the concept of natural selection and evolution (Goldberg, 1989). Inspired by natural evolution, techniques such as inheritance, mutation, selection, and crossover are introduced to GAs. A population of individuals for the optimization are generated routinely and evaluated using a fitness function. The general scheme of GAs are structured in Figure A.1.

Any implementation of GA for a particular problem must address several important issues; these include the initial population, the probability and the type of crossover, the probability and type of mutation, the stopping criteria, the type of selection operator, and the fitness function to be used. All these selections are inter-related and affecting the performance of GA. For the optimization problem in this research for estimating the parameters in the domain model, special mechanisms must be incorporated for the considerations of the linear constraints. These significant issues have been addressed in Chapter 4 in details.
Figure A.1 General Scheme of Genetic Algorithm
Appendix B. Traffic Regulations in Fitness Function

This appendix will address the consideration of traffic rules in formulating fitness function.

The influence of regulations on the planning paths is partially considered in the model of ship domain, i.e., the rules on collision-avoidance action in a close encounter. In addition, the requirements of preventing a succession of small alterations of course and/or speed, has been represented in the comfort component in the fitness function. In this section the level of compatibility of the navigational path with respect to some other items in COLREGs will be addressed as follows.

1) Navigation in Narrow Channel

The safety related to the narrow channel will be addressed specifically in accordance with requirements stipulated in COLREGs. When sailing in narrow channel, all the ships are required to keep to the outer limit of the channel lies on the starboard side of the vessel. Therefore, the cost function related to channel limit can be defined based on the actual distance to the outer limit of the channel as

\[ c_{ij}^d = G_{ij} \cdot e^{-\alpha \cdot (d_{ij} - \xi_j)} \]  

(b.1)

where \(d_{ij}\) is smallest distance between path segment \(i\) and limit of the channel \(j\); \(G_{ij}\) is a penalty value of encroachment to channel limit \(j\); and \(\xi_j\) is the minimum requirement of the distance between the ship to the channel limit \(j\); assuming that the minimum requirements to the starboard side \(\xi_s\), and to the port side \(\xi_p\) are different, i.e., \(\xi_s \leq \xi_p\) so that ships will stay to the starboard side if the channel is...
not sufficiently wide; and $\omega_{c,l}$ is a coefficient related to channel limit.

2) Regulations under TSS

Ships navigating in areas under Traffic separation Scheme (TSS) are regulated by the additional rules stipulated in COLREGs (1972). The vessels using TSS shall:

1. Proceed in the appropriate traffic lane in the general direction of traffic flow for that lane;
2. So far as practicable keep clear of a traffic separation line or separation zone;
3. Normally join or leave a traffic lane at the termination of the lane, but when joining or leaving from either side shall do so at a small an angle to the general direction of traffic flow as practicable;
4. A vessel shall so far as practicable avoid crossing traffic lanes, but if obliged to do so shall cross as nearly as practicable at right angles to the general direction of traffic flow.

Except for the item 2 which can be modeled similarly as the other common stationery constraints, the rest requirements will be converted in to formulas as follows.

Before incorporating the influence of TSS in the model, there are a few preparations to be done:

(a) Define the boundary of each traffic separation zone or traffic separation line;
(b) Define the start line $l_{st,k}$ and termination line $l_{tm,k}$ of the separation zone, and define the side line $l_{sd,k}$ of the separation zone $k$ where $k$ is the indicator of separation zones;
(c) Define a general direction of traffic flow for each separation zone, denoted by $\theta_k$.

For each segment $i$ ($i = 1, \ldots, l$) intersecting or locating in traffic separation zone, the regulations in TSS area are observed by optimizing the followings.

If the whole segment $i$ is located within a separation zone $j$, the difference between the heading of the ship and the direction of the general traffic flow should be minimized by

$$\text{Minimize } \Delta \theta_i = |\theta_i - \theta_k|$$  \hspace{1cm} (b.2)

where $\theta_i$ is the heading of ship in segment $i$ and $\theta_k$ is the general direction of traffic flow in separation zone $k$.

If any segment $i$ intersects the side line $l_{sd}$, the angle difference between the heading of the ship and the direction of the side line should be minimized by

$$\text{Minimize } \Delta \theta_{i, sd} = |\theta_i - \theta_{sd}|$$  \hspace{1cm} (b.3)

where $\theta_{sd}$ is the direction of side line $l_{sd}$.

If any segment $i$ passes through the boundary of the separation zone, i.e., cuts across consecutive lines (either on the side or the start and termination side), the ship
heading and the direction of the lines should be as perpendicular as possible. It is achieved by

$$Minimize \ \Delta \theta_{ij} = \pi / 2 - |\theta_i - \theta_j|$$  \hspace{1cm} (b.4)$$

where $\Delta \theta_{ij}$ is the angle between the ship heading and the direction of any line of boundary; $\theta_i$ is the direction of any line of the boundary of the separation zone.
Appendix C. Environmental Factors in Fitness Function

Ships are sailing under the presence of environmental fields, i.e., wind, current flow and tidal. The effect of these environmental factors may be considered when predicting the ship paths more accurately in the planning horizon.

1) Current

The actual ship speed, i.e., the speed over ground (SOG) is therefore a resultant speed of the speed through water (STW) and the environmental factors.

Under the effect of current, clearly the ship’s handling qualities are not significantly affected if the whole body of water in which she is manoeuvring is moving en masse together with the ship. Therefore the most characteristic influence of current is considered to be a change of the ship’s speed vector with respect to the ground which causes the direction of SOG to differ from the ship heading. The influence of this uniform current is modeled as an additional term to the kinematic relationships. Therefore, the speed over ground is a resultant velocity of ship speed through water and velocity of the current given by

\[ \vec{U}_{SOG} = \vec{U}_{STW} + \vec{U}_c \]  

(c.1)

where \( \vec{U}_{SOG} \) is the vector of SOG, \( \vec{U}_{STW} \) is the vector of STW, \( \vec{U}_c \) is the speed vector of cross current.
Then the ship’s drift angle, an angle between ship heading and direction of speed over ground vector over ground can be given by

\[
\beta = \tan^{-1}\left(\frac{\vec{U}_c \cdot \sin \alpha}{\|\vec{U}_{STW}\| - \|\vec{U}_s\| \cdot \cos \alpha}\right)
\]

(c.2)

where \( \beta \) is the drift angle due to the current effect; \( \alpha \) is the angle difference between the current and ship speed through water.

2) **Wind**

Wind exerts an additional force on the ship, and the effect is highly dependent on the ship’s superstructure and other geometric factors. The relative wind speed can be determined by transforming the real wind speed and the direction as

\[
\vec{U}_{wr} = \vec{U}_w + \vec{U}
\]

(c.3)

where \( \vec{U}_w \) is the vector of ship wind speed; \( \vec{U}_{wr} \) is the vector of relative wind speed.

The wind force on a ship is recommended as a second power of relative wind speed on ship (Passenier, 1989). And the acceleration of the ship is assumed to be a predetermined function of the wind force and the mass the ship as

\[
\vec{a}_w = f\left(m_s, \vec{F}_w\right)
\]

(c.4)

where \( m_s \) is the ship mass; \( \vec{F}_w \) is the wind force which is a function of \( \vec{U}_{wr}^2 \).
As a result, the ship speed under the presence of wind can be modified using kinematic function as

\[ \ddot{U} = \dot{U} + \ddot{a}_w \Delta t \] (c.5)

where \( \dot{U} \) is the original ship speed and \( \ddot{U} \) is the ship wind under the effect of wind after \( \Delta t \) time interval.

3) Tidal effect

The effect of tide on ship’s navigational path planning is highly related to the safety of ships, especially the risk of grounding accidents. It is because the vertical tidal variations are of huge importance to the available water depth underkeel of a vessel, i.e., Underkeel Clearance (UKC). Due to the fact that the present water level may not allow ships manoeuvring with a preset underkeel clearance, there may be restrictions of the time for ship waiting for a port entry or departure. Also the flow of the tide will at certain times make progress in a given direction difficult. The area where such flows of the tide often occur is named as the tide gate. Examples of such tide gates are entrances and narrow sections of bays or inlets, canals and other connecting waterways. The challenge for the navigators can be to plan a path that places the vessel in or near the tide gate at a suitable time and leaves enough time to pass through the entire area with a favorable tide.

The tidal effect can be similarly modeled as a time window of the arrival time at the area with restricted water level or the tidal gate. The time window could be variable with respect to different types of ships, displacement, and the time needed to pass
through the entire area. The time windows will constraint the path planning in dealing with the tidal effect.