International Journal of Naval Architecture and Ocean Engineering 12 (2020) 541–551

Contents lists available at ScienceDirect

International Journal of Naval Architecture and Ocean Engineering

journal homepage: http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Collision risk assessment based on the vulnerability of marine accidents using fuzzy logic

Yancai Hu [a], [b], Gyei-Kark Park [b], *

[a] Navigation College, Shandong Jiaotong University, China
[b] Faculty of International Maritime Transportation Science System, Department of Maritime Transport, MOKPO National Maritime University, South Korea

A R T I C L E I N F O

Article history:
Received 12 November 2019
Received in revised form
5 April 2020
Accepted 10 June 2020

Keywords:
Collision risk
Vulnerability
SMART-Navigation
Non-SOLAS ship

A B S T R A C T

Based on the trend, there have been numerous researches analysing the ship collision risk. However, in this scope, the navigational conditions and external environment are ignored or incompletely considered in training or/and real situation. It has been identified as a significant limitation in the navigational collision risk assessment. Therefore, a novel algorithm of the ship navigational collision risk solving system has been proposed based on basic collision risk and vulnerabilities of marine accidents. The vulnerability can increase the possibility of marine collision accidents. The factors of vulnerabilities including bad weather, tidal currents, accidents prone area, traffic congestion, operator fatigue and fishing boat operating area are involved in the fuzzy reasoning engines to evaluate the navigational conditions and environment. Fuzzy logic is employed to reason basic collision risk using Distance to Closest Point of Approach (DCPA) and Time of Closest Point of Approach (TCPA) and the degree of vulnerability in the specific coastal waterways. Analytical Hierarchy Process (AHP) method is used to obtain the integration of vulnerabilities. In this paper, vulnerability factors have been proposed to improve the collision risk assessment especially for non-SOLAS ships such as coastal operating ships and fishing vessels in practice. Simulation is implemented to validate the practicability of the designed navigational collision risk solving system.

1. Introduction

Due to the development of transportation, although high technologies of navigation are applied, the increasing of vessels causes the important water ways congested and high potential risk of marine collision accidents. Moreover, ship collision avoidance is getting more serious with the increase of dangerous cargo carriers, the size of vessels and the number of small ships. The acceleration of maritime collision accidents has become a great motivation to explore a significant solution to overcome the issues of marine safety of navigation.

To solve the issues of marine safety of navigation, Korea has promoted SMART-Navigation project (Ministry of Oceans and Fisheries, 2016) under the guidance of IMO's e-Navigation in order to provide safety services for International Convention for the Safety of Life at Sea (SOLAS) ships as well as non-SOLAS ships. SMART-Navigation is proposed to provide the Long-Term Evolution Maritime (LTE-Maritime) communication network for non-SOLAS ships in order to reduce the navigational risk. Aiming to improve the safety of Korean maritime traffic, it focuses on coastal navigation providing the following services: Sea traffic coordination leading to optimized maritime traffic flow; Maritime domain awareness enabling to detect risky situations that vessels may encounter with; Active and proactive maritime safety management pre-empting identified incident hazards; Remote monitoring enabling to evaluate ship system; maritime Telematics service delivering information related to navigational safety in seamless manners (SMART-Navigation Project, 2016).

However, ship navigation is a vast topic because it involves the numerous manoeuvres with many variants, and the theory behind ship manoeuvres can be explained but it is up to the practitioner to take full account of the influence factors in a real situation such as those affected by prevailing good weather or bad weather conditions, with tide or without tide (House, 2007). In this context, the navigational traffic conditions and environment should be taken into consideration. The study of marine vulnerability to reduce the

---

* Corresponding author.
E-mail address: gkpark@mmu.ac.kr (G.-K. Park).
Peer review under responsibility of Society of Naval Architects of Korea.

https://doi.org/10.1016/j.ijnaoe.2020.06.005

marine collision accidents acts as an important role in the project of SMART-Navigation (Kim, 2017). The services of the SMART-Navigation project include monitoring assistance service for high risk ships (SV10); remote monitoring on system onboard (SV20); optimal route planning (SV30); electronic navigational chart streaming for small vessels (SV40); pilot/tug assistance service (SV51); and maritime safety information service (SV52) (SMART-Navigation Project, 2016). To design the monitoring assistance service for high risk ships, the overview of this service is firstly proposed and described as Fig. 1. This service starts from the vulnerable situation awareness which consists of navigational vulnerability, environmental vulnerability and case-based vulnerability; after the vulnerable situation awareness, the risk assessment is conducted to obtain the vulnerability risk assessment, comprehensive assessment and route surveillance; at last, accident responses will be given such as short-term forecast, information propagation and information management.

Looking into collision accident, as there is still an upsurge of collision accidents relative to serious vessels, “encounter” and “probability” are key concepts involved. An encounter is an undesirable event, because when two vessels come close to each other the probability of a collision increases (Mou et al., 2010). The collision risk increases more promptly in the rough sea with large vulnerability of accident than in the calm sea. Therefore, a collision risk solving system integrating the vulnerability of traffic and environmental conditions is a desideratum for safe navigation in practice. For solving the collision risk, the concept of maritime vulnerability can be used to indicate the probability of accidents revolving additional traffic factors such as weather condition and congestion. It is defined as the properties of a transportation system that may weaken or limit its ability to endure, handle and survive threats and disruptive events that originate both within and outside the system boundaries (Asbjornslett, 1999).

So far, qualitative studies on collision risk assessment have been carried out for the significant development of automatic and intelligent navigation. It is well-known that the method of collision risk assessment can be performed by either detecting possible violation of ship domain, or defining a collision risk index based on DCPA, TCPA, ship domain and others such encounter angle and ratio of speed. However, little attention has been paid to deliberate the traffic and environmental context of the vessels in approaching each other for non-SOLAS ships. This paper seeks to address a way to investigate marine collision accidents with a view on the causes of vulnerability factors. Vulnerability indicates the probability of having casualties under the restrictions of such as weather, waterway conditions and fatigue factors. Hence, the aim of this paper is to design a model in which the vulnerability will be considered to improve collision risk assessment. It helps to alleviate the restrictions of coastal waterway for vessels including non-SOLAS ships to operate an effective collision risk assessment and provide a promising applicability of the service in the SMART-Navigation project.

The legend of this paper is divided in the following sections: section 2 illustrates the previous collision risk researches; in section 3 The framework of collision risk solving system based on vulnerability is designed; section 4 describes the coastal traffic situations along Korea and implements the simulation of collision risk detection based on vulnerabilities; finally, in section 5, the concluding remarks are given.

2. Collision risk researches

Large and growing quantities of researches have investigated the collision risk assessment. Hwang (2002) described a weighted sum of squares of DCPA and TCPA as the collision risk index which was firstly proposed for collision avoidance expert system. When the collision risk reaches a pre-set threshold value, the action of collision avoidance must be conducted. Further, Lisowski (2001) explored collision risk considering more safety factors such as the distance between the own ship and the target ship, the safe distance of approach, and the necessary time to plan. The state of visibility at sea, dynamic length, beam of ship and a kind of water region are taken into consideration thus to reflect the current situation dynamically and adaptively. Moreover, a more general concept of collision risk which was revealed by Szlapczynski (2006) was derived from ship speed, course, distance and the concept of ship domain. This presented measure is flexible to be applied to combine with any given ship domain to obtain the derivation for collision risk assessment.

Besides, fuzzy logic has been proved to be suitable and effective in dealing with linguistic representation and subjective concept. Hasegawa (1987, Hasegawa et al., 1989) built fuzzy model for the collision risk using the fuzzy inference system by using DCPA and TCPA as input values. Triangular-type membership functions are applied for fuzzy calculation convenience. Singleton-type membership functions are used at consequence part to simplify the defuzzification process by Lee and Rhee (2001) and develop a fuzzy collision avoidance system by using the expert system and action space search. Then, an autonomous navigation algorithm was proposed by Lee et al. (2004) using fuzzy logic satisfying COLREG guidelines. The modified virtual force field method, derived from the field of mobile robotics in addressing the problem of obstacle avoidance, is applied for eight track-keeping and collision avoidance models based on the fuzzy rules. Additionally, Kao et al. (2007) indicated a fuzzy logic method developed for collision risk assessment system to generate models of a guarding ring and danger index based on ship length, speed and weather conditions. The fuzzy domain of the guarding ring was calculated using three input linguistic variables: length of ship, speed of ship, sea state and one output linguistic variable: D (radius of guarding ring). While two guarding rings overlap, a danger index was calculated for the two ships to keep a safe encountering to enhance the VTS decision-

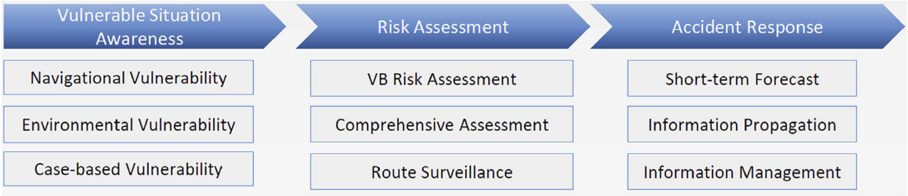

Fig. 1. Monitoring assistance service for high risk ships.
Source: Authors.

making abilities by providing an alerting system for collision risk prediction. In the study of Ahn et al. (2012), the fuzzy inference system was combined with an expert system for collision avoidance. One calculation method of the collision risk was proposed by using neural network. Firstly, a simply constructed fuzzy reasoning system was combined with the database of an expert system where the navigator's knowledge is stored in. Then, the fuzzy reasoning system was used to calculate the degree of the collision risk. The adaptive network-based fuzzy reasoning system, namely a general neuro-fuzzy system, was used to reform the fuzzy membership functions and rules. Furthermore, in Zhou and Zheng (2019) a novel dynamic fuzzy ship domain that considered the factors associated with both own ship and other ships for determining the spatial collision risk for the navigational situation as part of a ship collision avoidance system.

However, the collision risk of non-SOLAS ships tends to be affected by the impacts of environment and traffic conditions and it is also difficult to assess these factors. When a ship is navigating at sea, it may cause collisions because of the influence of the ship changing dynamic property as well as the varying winds, waves, currents etc. Besides, collision accidents are increasing as the ascent of ship size and speed under the severe conditions of traffic and environment especially related to the fishing boats or other small ships (An, 2016).

Fortunately, the factor of weather condition was generally considered to develop collision risk assessment system (Kao et al., 2007). Using spatial mapping and time analysis algorithms, the results for the vessels collision alert system were calculated according to navigational safety information such as AIS data, harbor weather reports. In general, seasoned navigators defined the safety range and estimate a clearance (e.g. two nautical miles) by experience to maintain between own ship and any other target ship. However, the clearance is an imprecise value that was affected by ship manoeuvring, ship speed as well as traffic conditions. For busy water areas, Mou et al. (2010) focused on the analysis of statistical AIS data for the collision avoidance for the involved ships and investigated the actual behaviour of ships. Linear regression models were used to identify the correlation between the key indicator CPA and ship's size, speed and course. The risk models were designed into two categories called as basic risk such as ships state, weather conditions and dynamic risk which was related to TCPA, CPA and encounter angle. Thus, the inosculation of weather conditions and traffic congestion are implemented for collision risk assessment.

Additionally, based on John and Osue (2017), a specific model was constructed to analyse the identified risk factors, such as failure of thruster, human errors, extreme weather and fatigue. The selection of such risk factors was based on extensive discussions with experts and a robust literature review. These risk factors were chosen because they were regarded as the most significant ones specifically associated with the accidents for collision risk. Among the factors, the extreme weather acted as highly important factors for the rendered collision risk model and situation. For the heavy traffic areas, a real-time ship collision avoidance system using six-dimensional manoeuvring modelling group (MMG) model was designed by Fang et al. (2018). Different traffic factors were considered for the simple and complex cases of collision avoidance including multi-ship encounter conditions. The parameters of ship safe domain could be adjusted for heavy traffic areas and open sea. The ship collision avoidance model effectively was designed for different cases especially in a heavy traffic area.

Based on the review of the previous studies, most of them focus on the investigation of basic collision risk using the main factors TCPA and DCPA, some of the studies consider encounter angel to meet the requirement of COLREG and others deliberate the ratio of speed, related bearing. Although many studies consider the environmental conditions, there is still not comprehensive for the real navigation to reduce the collision accidents especially of the Non-SOLAS ship. To improve the collision risk assessment, marine vulnerability will be combined to solve the SMART-Navigation issues. In improve the basic collision risk, vulnerability of maritime accidents is considered as "auxiliary risk" illuminated by the application of the study (Mou et al., 2010). It depends on size, weather, traffic conditions and navigational conditions, etc. It is the average possibility of collision risk for ships in the sealing area. The determination of vulnerability is the result of many years investigation by analysing the collisions in practice. The vulnerability solving system will be the main subject of this study. It is necessary to consider the traffic and environmental factors to reduce collision accidents. Therefore, this study acts as a supplement to the body of literature in the way to provide navigational collision risk for non-SOLAS ships including small vessels as well as fishing ships in the specific coastal waterways.

3. Collision risk solving system: a theoretical framework

Marine vulnerability can be considered as "auxiliary risk". It is the additional possibility of risk which can be detected by the experienced officer for ships in the sailing area. The determination of this auxiliary risk is derived from the results of many years of investigation related with real operational environment conditions. All the parameters included are related to the vulnerabilities which should be considered following the procedure of collision risk. Thus, the navigational collision risk comprehensively combing vulnerability and basic collision risk in real operation, is calculated as

$$\text{Collision risk} = \text{Basic collision risk} \circ \text{Vulnerability} \tag{1}$$

The framework of collision risk solving system based on vulnerability contains four modules in Fig. 2. Firstly, DCPA and TCPA, which are still popular factors for evaluating collision risk and supporting decision making, are used to calculate the collision risk by the information of own ship course (OSC), own ship speed (OS), target ship course (TSC), target ship bearing (TB), ship speed (S) and distance (D) between the encountering ships. Then basic collision risk will be obtained based on the membership functions and rules of DCPA and TCPA (see Fig. 3).

Firstly, the purpose of the vulnerability module is to identify the importance of the vulnerability factors leading to marine accidents and calculate the vulnerabilities. Secondly, based on the brainstorming of experts in various workshops involving captains of coastal cargo vessels, fishing boats, other small ships in Korea, ten vulnerability factors of narrow waterways, weather deterioration, strong tidal currents, accident-prone area, sea traffic congestion area, visibility restriction, low depth/reef/watermark, operator fatigue, fishing operating area, tugboat operating area are detected. However, four factors were eliminated after further analysis and research considering the necessity and feasibility of application for collision risk. Finally, six vulnerability factors are involved in accident of coastal ships summarized from expert opinions. The variables of the basic collision risk and vulnerability are listed in the questionnaire simultaneously from forty ship captains and officers and eighteen experts. The profiles of the representative experts and their interested fields are listed as Prof. Gyei-Kark PARK, maritime information system; Prof. and Captain Qiang Zhang, ship robust control; Prof. Geonung Kim, maritime computer engineering; Dr. Gi-Jong Jo, maritime technology; Dr. Jagan Jeevan, Maritime Studies; Dr. and officer Delong Wang, Maritime simulation and collision avoidance; Prof. Serng-Bae Moon, maritime safety assessment; Dr. Xiangfeng Yang, statistics, fuzzy and uncertain

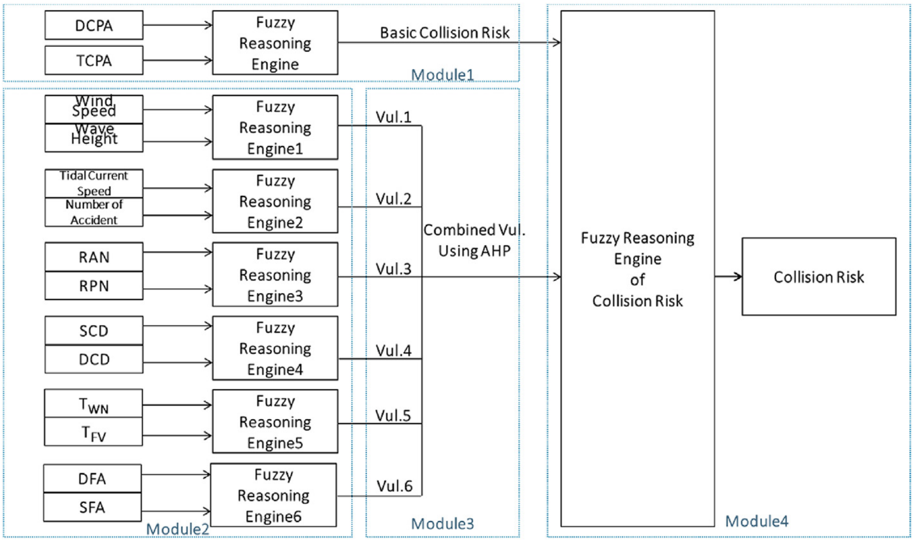

Fig. 2. Structure of the collision risk solving system
Source: Authors.Note: Considering eight reasoning engines with too many rules will cause the burden of the total system, thus only the most important two variables are adopted for each reasoning engine.

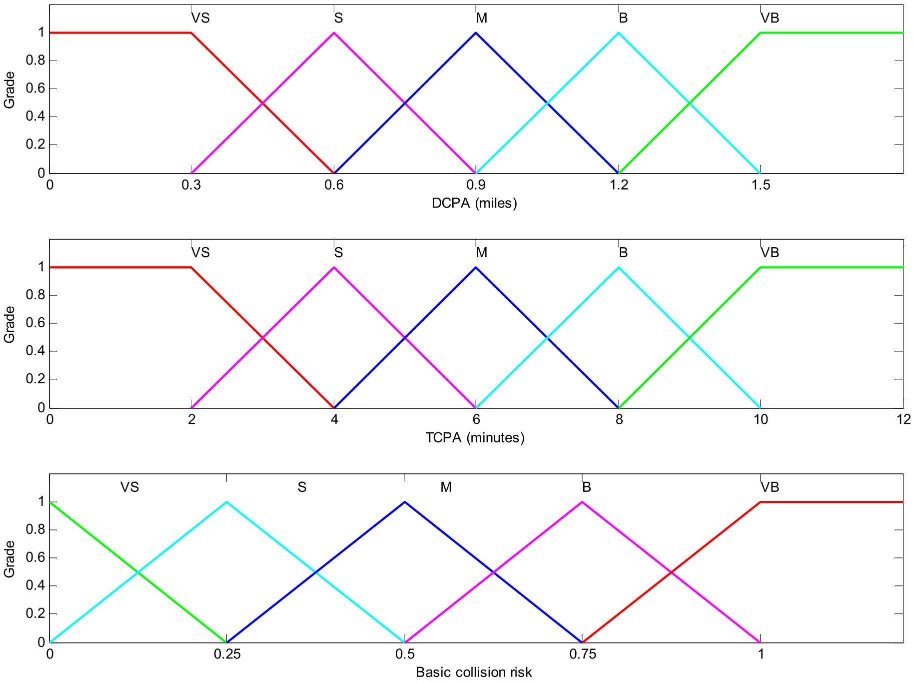

Fig. 3. Membership functions for DCPA, TCPA and basic collision risk
Source: experts and captains.

theory.

Fuzzy reasoning engines are used to calculate vulnerabilities of ship considering bad weather, tidal currents, accidents prone area, traffic congestion, operator fatigue and fishing boat operating area as influence factors for the coastal situation. Then, after the results of six factors of vulnerability are obtained, this collision risk solving system seeks to combine them as one synthesis using AHP method. The results can not only show the rank of each vulnerability but also the average value. It clearly provides the information of traffic and environmental conditions which are difficult to combine and judge.

Finally, the basic collision risk and combined vulnerability are integrated in fuzzy reasoning module four to gain the collision risk. Because basic collision risk and combined vulnerability are different concepts, it is not possible to add two dimensions mathematically, thus fuzzy logic is also used to infer the collision risk.

3.1. Basic collision risk module

In module one, a popular and common method is taken into consideration for solving the basic collision risk using DCPA and TCPA which are significant input variables that can interactively determine the possibility of that the target ships will collide with own ship if in the remaining time the right alteration of heading is not executed. Note that to evade a possible collision, the DCPA and TCPA must be considered at the same time.

$$(\text{DCPA},\ \text{TCPA}) \rightarrow \text{Basic collision risk} \tag{2}$$

A succinct fuzzy reasoning model is used and the membership functions for DCPA, TCPA and basic collision risk are classified as five linguistic values. The calculation of basic collision risk contains two inputs and one output, which is determined by the reasoning rules. The reasoning rules are listed for the fuzzy logic reference engine in Table 1.where VB is very big, B is big, M is medium, S is small and VS is very small.

The inputs of DCPA & TCPA and the output of basic collision risk have five linguistic variables. 25 fuzzy rules are designed to determine the basic collision risk. As DCPA and TCPA are getting smaller, the basic collision risk will get bigger.

The process of fuzzy inference is performed by four steps: fuzzification of DCPA and TCPA, rule evaluation, aggregation of the rule outputs and finally defuzzification. The final output of this reasoning engine is basic collision risk which a crisp number obtained by using centre of gravity method.

3.2. Vulnerability modules

In coastal waterway on the Korean coast, the additional environment and traffic factors affect the degree of collision risk for small ships. Coastal narrow waterway is a waterway that passes between land areas on both sides with characteristic of fast tide and instantaneously changed water flow. In addition, traffic congested areas, fishing boats operating areas, accident prone areas and bad weather are distributed in most of the coastal waterways and the risks of marine accidents always exist. The causes of these collision accidents are considered not only because of collision risk factors but also the vulnerability factors. In order to obtain navigational collision risk, the solutions of six vulnerabilities are summarized for vulnerable awareness as below with full consideration of the opinions of experts and ship captains.

In this section, six pairs of variables take place at the same time and are independent. For each vulnerability factors, two important variables having strong relation with each other are considered. The values of vulnerability factors will be calculated and shown to officer as reference to do further collision avoidance actions.

To solve the problem of collision at sea, DCPA and TCPA are treated as the most important variables to judge the possibility of basic collision risk. Five membership functions and 9 rules can provide more accurate result. While for the vulnerabilities less important than basic collision risk, so three membership functions are adopted to design as below.

3.2.1. Bad weather

The research of vulnerability starts form the bad weather. Worsening weather is caused by weather conditions such as strong winds, typhoons and storms etc. The operation and trajectory of non-SOLAS ships including fishing boats can be affected by bad weather condition which is one reason of collision accidents. Hence the vulnerability of bad weather is investigated based on the combination of Wind Speed (WS) and Wave Height (WH) by using the following fuzzy membership functions and reasoning rules. Wind speed and wave height are chosen as the main impacts to refer the vulnerability of bad weather.

$$(\text{WS},\ \text{WH}) \rightarrow \text{Vulnerability (1) of bad weather} \tag{3}$$

Triangular membership functions of bad weather for about 25-meter non-SOLAS ships are described as wind speed (m/s): “small”=(0 0 10), “medium”=(0 10 14), “big”=(10 14 14), wave height(m): “small”=(0 0 1.75), “medium”=(0 1.75 3), “big”=(1.75 3 3), and consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). The values of 0/10/14 m/s and 0/1.75/3 m can be taken to correspond the linguistic values of small, medium, big for wind speed and wave height, respectively. According to the opinions of experts and captains, fuzzy rules are designed for the fuzzy engines where the wave height is considered as a more important factor than the wind speed as shown in Table 2.

3.2.2. Strong tidal currents

The sea areas in the coastal waterways have the high velocity tidal current and the direction is easily changed. Many accidents happened in connection with strong tidal current. After collision accidents happen, greater losses result from the difficulty in rescue. The input variables tidal current speed and number of accidents in the past ten years are used to infer the vulnerability.

$$(\text{Tidal current speed},\ \text{Number of accidents}) \rightarrow \text{Vulnerability (2) of strong tidal current} \tag{4}$$

Fuzzy membership functions for strong tidal current are illustrated as tide speed (knot/h): (0 0 2), (0 2 4), (2 4 4), number of accidents: (20 20 30), (20 40 60), (40 60 60), consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). The fuzzy reasoning rules involving static and dynamic explanation for the tidal current are shown in the following Table 3.

3.2.3. Accident prone area

Accident prone areas always have a greater than average number of accidents. The vulnerability of accident prone area is identified based on the observed number of collision accidents and regression analyses. The vulnerability can be calculated by considering not only the dynamic data but also the static data as

$$(\text{RAN},\ \text{RPN}) \rightarrow \text{Vulnerability (3) of accidents prone area} \tag{5}$$

where RAN is ratio of accident number per hour in a day the past 10 years. RPN is ratio of passing ship’s number per hour.

Fuzzy logic membership functions for accidents prone area are described for ratio of accident number: (0 0 50), (0 50 100),

Table 1
Reasoning rules of DCPA, TCPA and basic collision risk.

DCPA	TCPA				
	very small	small	medium	big	very big
very small	VB	VB	B	B	M
small	VB	B	B	M	M
medium	B	B	M	M	S
big	B	M	M	S	S
very big	M	M	S	S	VS

Source: experts and captains

Table 2
Reasoning rules for the vulnerability of bad weather.

Wave height	Wind speed		
	small	medium	big
small	VS	S	M
medium	M	M	M
big	M	B	VB

Source: experts and captains.

Table 3
Reasoning rules for the vulnerability of strong tidal current.

Tidal current speed	Number of accidents		
	small	medium	big
small	VS	S	M
medium	S	M	B
big	M	B	VB

Source: experts and captains

Table 4
Reasoning rules for the vulnerability of accidents prone area.

RPN	RAN		
	small	medium	big
small	VS	S	M
medium	S	M	B
big	M	B	VB

Source: experts and captains.

(50 100 100), ratio of passing ship's number: (0 0 50), (0 50 100), (50 100 100), consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). Based on the fuzzy logic membership functions, the reasoning engine utilizes the reasoning rules of two variables RAN and RPN representing the static and dynamic information of accident prone area as that shown in Table 4.

3.2.4. *Traffic congestion*

Traffic congestion areas have the property with large number of ship and a high risk of accident. The traffic congestion can lead to collision accidents due to the increasing traffic volume. The static congestion degree and dynamic congestion degree are selected to infer the vulnerability.

$$(\mathrm{SCD},\ \mathrm{DCD}) \rightarrow \text{Vulnerability } (4) \text{ of traffic congestion} \tag{6}$$

where SCD is static congestion degree, DCD is dynamic congestion degree.

The Static Congestion Degree (SCD) is the number of vessels passing through a narrow waterway in 1 h in a small-unit marine zone. The number of passing vessel is collected within 72 h before a specific day.

$$SCD = \frac{\text{number of passing vessels per 3 days}}{72 \times \text{number of small marine zone}} \tag{7}$$

The Dynamic Congestion Degree (DCD) is the number of vessels passing through a narrow waterway in a specific 1-h in a small-unit marine zone.

$$DCD = \frac{\text{number of passing vessels per hour}}{\text{number of small marine zone}} \tag{8}$$

DCD is considered as more important variable than SCD because it shows the current possibility of an accident occurred while SCD is an average congestion degree in the waterways in the past three days. The higher the value is, the more crowded the waterway will be.

Fuzzy logic membership functions for traffic congestion consist static congestion degree: (0 0 0.5), (0 0.5 1), (0.5 1 1), dynamic congestion degree: (0 0 0.5), (0 0.5 1), (0.5 1 1), consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). Similarly, the reasoning rules are designed and shown in Table 5.

3.2.5. *Operator fatigue*

Operator fatigue is a condition that can cause accidents with the accumulation of fatigue of the operator due to long-time operating. In the process of navigation with the operator fatigue, poor decisions and errors often lead to collision accidents by the reason that fatigued crew fail to watch, take actions, communicate or coordinate their activities with others. Generally, the time of working navigation and tonnage of fishing vessel are chosen to quantize operator fatigue.

$$(\mathrm{T_{WN}},\ \mathrm{T_{FV}}) \rightarrow \text{Vulnerability } (5) \text{ of operator fatigue} \tag{9}$$

where T_{WN} is the time of working and navigation, T_{FV} is the tonnage of fishing vessel.

Considering the tonnage of fishing boats and other small ships in coastal area, the interpretation of fuzzy logic membership functions for operator fatigue are shown as below, tonnage of fishing vessel (ton): (0 0 5), (0 5 10), (5 10 10), as time of working and navigation (hour) as: (0 0250), (0 250 500), (250 500 500), consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). In the following Table 6, the reasoning rules for T_{WN} and T_{FV} are given.

3.2.6. *Fishing boats operating area*

In the fishing boats operating areas, fishery, fishing line, trawl net and other fishing gears are used to limit traffic performance, which can cause collision accidents between cargo ship and fishing boats, also other accidents such as obstructing the route of other ships or netting the propeller. The route planning of the merchant ships is usually designed to avoid traditional fishing grounds and areas with dense fishing fleets. In this case, the fishing boat activities will be analyzed to discover the fishing areas to obtain the input variables of the reasoning engine. Then fuzzy C-mean clustering method is used to cluster the fishing boats areas based on the historical AIS data of fishing boats including latitude, longitude, ship speed and number of fishing boats trajectory.

$$(\mathrm{DFA},\ \mathrm{SFA}) \rightarrow \text{Vulnerability } (6) \text{ of fishing boats operating area} \tag{10}$$

where DFA is distance to the centre of fishing Area, SFA is size of fishing area.

Fuzzy logic membership functions for fishing beats operating area are noted as distance to the centre of fishing area (mile): (0 0 10), (0 10 20), (10 20 20), size of fishing area (mile): (0 0 15), (0 15 30), (15 30 30), consequence: (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1). The reasoning rules are described in Table 7.

Table 5
Reasoning rules for the vulnerability of traffic congestion in the coastal waterways.

DCD	SCD		
	small	medium	big
small	VS	S	M
medium	M	M	M
big	M	B	VB

Source: experts and captains

Table 6
Reasoning rules for the vulnerability of operator fatigue.

T_{FV}	T_{WN}		
	small	medium	big
small	M	S	VS
medium	B	M	M
strong	VB	VB	B

Source: experts and captains

Table 7
Reasoning rules for the vulnerability of fishing boats operating area.

SFA	DFA		
	small	medium	big
small	M	S	VS
medium	B	M	S
big	VB	B	M

Source: experts and captains

This procedure (3–10) can be referred to in other navigational situation, but the parameters of the fuzzy model may cause deviation from area to area and also from ship to ship. Tune should be implemented to meet the actual situation.

3.3. *Solution for combined vulnerability*

The purpose of the part is to comprehensively assess the interacting vulnerabilities that significantly increase navigational collision risk. To apply AHP method, the necessary information regarding the contextual relation of the selected factors is illustrated in the questionnaire survey with the respondents of experts (Emrah et al., 2012). AHP method is a multipurpose decision-making method to solve decision making problem involving multiple goals and is utilized by Sahin and Senol (2015, 2017) to analyse marine accidents and shipping technology selection. The study (Do et al., 2018) from research team applies AHP to measure the weight of vulnerability factors under consideration. The respondents based on the importance scale from 1 to 9 to evaluate the preference of factors. Twenty captains and officers in coastal ships and ten experts related to maritime universities are selected. Basing on the survey results, an important matrix S_{ij} is built using formula as below.

$$[S_{ij}]_{6\times 6} = \sum_{k=1}^{20} [\frac{S_{ij}^k}{20}]_{6\times 6}, (i,j = 1,2,...,6; \quad k = 1,2,...,20) \tag{11}$$

where S_{ij}^k indicates how much higher or lower the importance of S_i is when compared with S_j.

The vulnerability factors in the matrix are consist of S1 (Bad weather), S2 (Strong tidal currents), S3 (Accident prone area), S4 (Sea traffic congestion area), S5 (Operator fatigue) and S6 (Fishing boats operating area) shown in Table 8.

According to Table 9, the result of consistency ratio is calculated to be 0.09 as below, which is less than 0.1.

$$CR = \frac{CI}{RI} = \frac{0.11412}{1.24} = 0.09 < 0.1 \tag{12}$$

where CR is consistency ratio, CI is consistency index, RI is random consistency index.

Table 8
Importance matrix of vulnerability factors.

Factors	S1	S2	S3	S4	S5	S6
S1	1.00	3.67	1.67	3.67	0.33	7.00
S2	0.29	1.00	0.33	1.44	0.18	4.33
S3	0.78	3.00	1.00	3.00	0.29	6.33
S4	0.29	1.44	0.51	1.00	0.18	4.33
S5	3.00	5.67	3.67	5.67	1.00	9.00
S6	0.14	0.24	0.16	0.24	0.11	1.00

Source: experts and captains

Table 9
Random consistency index.

n	1	2	3	4	5	6
RI	0.00	0.00	0.58	0.90	1.12	1.24

Source: authors

This indicates that the matrix has proper consistency and the error of the questionnaire answer is less than 10 percent. The following table shows the weights and priority of the vulnerability factors.

Based on the results, the combined vulnerability is calculated as

$$Combined \ Vul = \sum_{i=1}^{6} \mathrm{Vul}_i \times w_i \tag{13}$$

3.4. *Collision risk*

The risk will be calculated using two input variables as shown in Table 11 in which the collision risk is considered as main factor, while vulnerability is of subordination (see Table 10). Fuzzy logic is also used to get the collision risk because it is not possible to obtain the fusion of collision risk and vulnerability in mathematical way.

The membership functions of collision risk, combined vulnerability and consequence are designed as (0 0 0.25), (0 0.25 0.5), (0.25 0.5 0.75), (0.5 0.75 1), (0.75 1 1) and the rules of fuzzy reasoning in Table 11 are designed in the way of on board officer's thinking that the small value of combined vulnerability affects lightly the big value of basic collision risk.

4. Traffic situations and application

Korea is mostly surrounded by water, has many small islands around and the large number of successive mountain ranges that crisscross the peninsula and running deep below sea level to create a gentle coastal terrain. This natural condition has created various narrow waterways and made the characteristics of the South Korean coast become quite complex. Fig. 4 shows 4408 offshore accidents in 2015 and 2016. Most marine accidents occur inside the territorial sea. The accidents of collision, contact, and grounding occur mainly in coastal areas close to the land.

4.1. *Traffic situations along Korean coastline*

According to statistical yearbook of maritime distress by Korea coast guard (Korean Marine Security Safety Division, 2016), 69.5 percent of marine casualties occur in coastal waters. Besides, 73 percent of marine casualties occur in small vessels of less than 100 tons including fishing vessels. These involve small ships which are classified as non-SOLAS ships, which are poor in navigational circumstances without the nautical charts, even no radio equipment,

Table 10
Weight and priority of vulnerability factors.

Factors	Weight	Rank
S1	0.2125	2
S2	0.0804	5
S3	0.1688	3
S4	0.0844	4
S5	0.4264	1
S6	0.0275	6

Source: authors

Table 11
Reasoning rules for collision risk.

Collision risk	Combined Vulnerability				
	very small	small	medium	big	very big
very small	VS	VS	S	M	B
small	S	S	M	B	VB
medium	M	M	B	VB	VB
big	B	B	VB	VB	VB
very big	VB	VB	VB	VB	VB

Source: experts and captains

no mean position fixing system and communications with SOLAS ships. Additionally, there are many islands, fishing operating areas in coastal waterways which caused ships more prone to collision accidents. The surveys from the statistical yearbook of maritime distress (Korean Marine Security Safety Division, 2017) show that the number of collision accidents is 426, 13.5 percent of total 3160 accidents. Comparing to that of 311 in 2016 and 225 in 2013, it increased 37 percent and 89 percent, respectively. The number of accidents categorized by ship types shows more than 55.6 percent are related to the fishing boats comparing to that 277 in 2013, it increased over 200 percent to 1756. Among the navigation issues, collision avoidance is one of the most urgent topics to be considered.

There are about 159 coastal narrow waterways in Korea which can be divided into 6 regions (2018), including Gyeongiman, Cheosuman-Anmagundo, Mokpo Port and the nearby, Wando-Thongyoung, Thongyoung-Ulsan and Jeju island in Fig. 4. For recent years, the number of accidents in coastal waterway is quite big and the majority belongs to fishing vessels with engine malfunction reason account for 26 percent, following by collision accidents, safety disturb, grounding accidents, respectively. It was also surveyed in Kim paper (Kim et al., 2014) that the highest current speed waterways in Korea were Myeongnayang, Maenggol, Geocha, Heonggan, Northern of Jeongdeung-hae, Jangjuk, Daebang waterways. In particular, the maximum current speed of Myeongnayang waterway was 10.3–11.5 knot (KHOA, 2013), which was the fastest one on the Korean sea areas. In the recent 9 years (2008–2016), there were 99 marine accidents in the high current speed waterways, including 16 collision accidents, 21 grounding accidents, 20 engine troubles and the losses of cargoes.

4.2. Application of integrated collision risk solving system

The proposed algorithm will be tested with simulation to prove its validity. In the simulation, the course and speed of own ship (OS) are 10° and 14 knots respectively. Four TSs (A, B, C, D target ships) in the vicinity of own ship in coastal waterway are shown in Table 12, the information of course, speed, bearing and distance which are used to calculate DCPA and TCPA.

Ten areas are chosen for simulation from 159 coastal waterway areas as they have the difference in traffic environment: 1. geumosudo, 2. daebangsudo, 3. baeglyeongdo, 4. incheonnamhang, 5. ibpado(asanman), 6. daesanhang, 7. jejuhang, 8. seongsanpo, 9. seogwipo, 10. ieodo. The collected useful statistic parameters

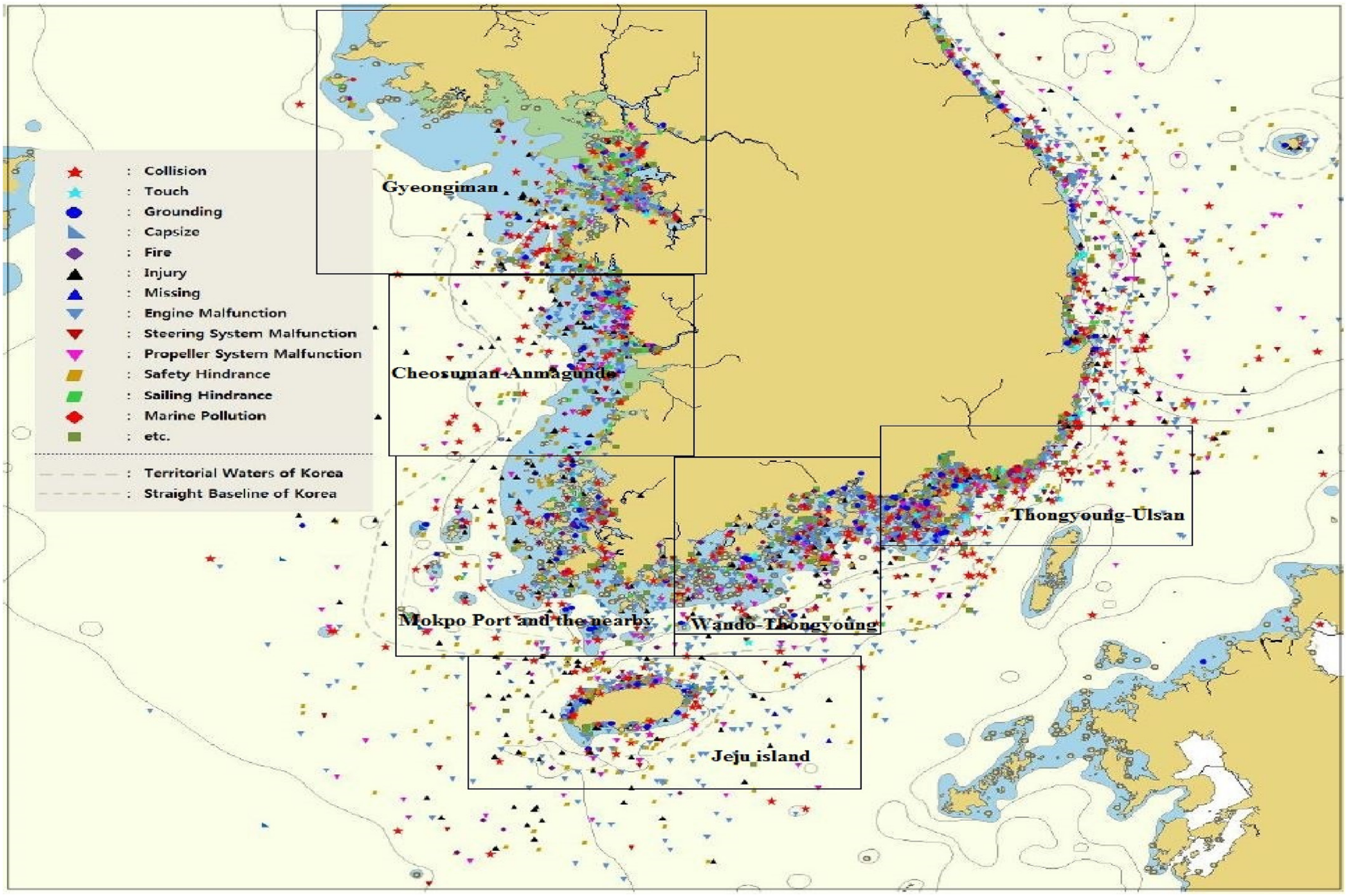

Fig. 4. Marine casualties (2016–2017).

Table 12
Details of target ships in the vicinity of own ship.

Ship	Course (degrees)	Speed (knots)	Bearing (degrees)	Distance (miles)	DCPA (miles)	TCPA (minutes)
A	240	30	050	5.0	0.46	7.38
B	260	10	025	7.5	4.22	9.83
C	150	25	350	6.1	1.43	9.15
D	087	37	280	6.5	0.12	11.5

Source: authors

Table 13
The inputs of vulnerability factors.

Coastal Waterway	Bad Weather		Strong Current		Accident Prone Areas		Traffic Congestion		Operator Fatigue		Fishing Area	
	WS	WH	CS	NA	RAN	RPN	SCD	DCD	TWN	TFV	DFA	SFA
1	09	1.0	3.3	4	20	13.5	0.10	0.09	02	0.2	22.91	7.71
2	13	2.5	4.0	81	30	2.34	0.53	0.38	40	0.4	22.91	18.62
3	12	2.5	2.4	10	10	4.71	0.00	0.01	100	0.6	30.83	11.74
4	12	2.5	1.8	37	11	4.35	0.36	0.32	123	0.8	14.03	16.31
5	13	2.5	2.0	184	09	5.87	0.04	0.06	800	10.0	14.03	22.24
6	12	2.5	1.5	20	05	4.26	0.23	0.96	227	1.2	30.83	11.84
7	13	2.0	1.2	20	00	5.04	0.11	0.08	145	1.4	12.00	22.24
8	13	2.5	1.6	52	08	7.10	0.15	0.27	188	1.6	10.00	22.24
9	13	2.5	1.0	19	11	0.96	0.04	0.02	365	5.0	8.00	22.24
10	13	2.5	1.7	8	38	4.26	0.01	0.01	271	1.0	6.00	22.24

Source: authors

related to accident of collision will change while the ships sail to a different sea area. The input variables are detected and collected in Table 13. The navigational risk combines with the results of basic collision risk based on TCPA and DCPA and vulnerability. The threshold value α of the system is designed as to alert a collision.

The results of six vulnerabilities are listed in Table 14. The rank of the vulnerabilities will be shown to the captain of the own ship as reference. The biggest value and combined vulnerability will be taken into account for navigational collision risk assessment.

In the coastal waterway 5 ibpado (asanman), the combined vulnerability is bigger than others, because the weighted results of bad weather and operator fatigue lead to big vulnerability. For each waterway, the vulnerability with biggest value will be given attention. Since the vulnerabilities of bad weather, accident prone area and operator fatigue are the most important ones, if one of the values is over 0.9, then other vulnerabilities will not be considered. The situation will be defined as very big risk. Else the combined vulnerabilities are generally utilized to calculate the navigational collision risk. If the value of combined vulnerability is small such as 0.39, it will not affect the basic collision risk with a relative big value as 0.62, but still can increase relative small ones such as 0.07 or 0.17 as shown in Table 15.

Table 14
The results of navigation vulnerability factors.

Coastal Waterway	Vul1	Vul2	Vul3	Vul4	Vul5	Vul6	Combined Vul.
1	0.37	0.50	0.25	0.20	0.49	0.19	0.39
2	0.75	0.96	0.22	0.52	0.52	0.32	0.55
3	0.71	0.40	0.16	0.05	0.57	0.22	0.46
4	0.71	0.51	0.16	0.37	0.57	0.42	0.50
5	0.75	0.79	0.16	0.13	0.75	0.52	0.60
6	0.71	0.17	0.12	0.47	0.65	0.22	0.51
7	0.71	0.15	0.08	0.21	0.56	0.56	0.45
8	0.75	0.66	0.17	0.28	0.58	0.62	0.53
9	0.75	0.14	0.13	0.11	0.66	0.65	0.50
10	0.75	0.25	0.25	0.06	0.70	0.67	0.55

Source: authors

In the application, the characteristics of targets A, B, C, D are generally considered using same combined vulnerability which is helpful for the officers to judge collision situation. The purpose is to verify the influence of vulnerability upon collision risk.

The vulnerability and basic collision risk of four ships can be seen from Table 15. The proposed algorithm for navigational collision risk solving system is simulated to validate the performance in the complex traffic scenario. The conditions of the vessels and environment are listed in Tables 12 and 13. For instance, the own ship is involved in an encounter with four target ships in which they are crossing with each other. Under the condition of coastal water 5, the collision risk is detected for a potential collision for ship A as the value is 0.73. So that, ship A is considered as an alert of collision, because the threshold value 0.70 is exceeded by the detected value. However, the collision risk using DCPA and TCPA is 0.62 which fails to alert for collision risk and may lead to miss the best time to take collision avoidance. When the ships go through the coastal waterways, it is dangerous to ignore the influence caused by traffic conditions and environment may lead to an accident.

Compared with traditional collision risk assessment, this algorithm is more reasonable for collision assessment as more factors are integrated. Collision accidents could be effectively prevented if this navigational collision risk is suggested to the officers and the cadets who have insufficient sea experience and navigation competency. The effectiveness of this system will be test in real environments and checked under the supervision of experienced officers and experts. Through their judgment, the fuzzy method and membership function will be modified.

5. Conclusions

This paper proposed a comprehensive estimation to investigate potentials for navigational collision risk solving system and apply efforts to the implementation of e-Navigation solutions for non-SOLAS ships. A fuzzy methodology for navigational collision risk based on marine accident vulnerability using 6 factors was carried

Table 15
Results of the collision risk in the coastal waterways.

Target ships	Combined vulnerability	Basic collision risk	Collision risk	Target ships	Combined vulnerability	Basic collision risk	Collision risk
A	0.39	0.62	0.62	A	0.51	0.62	0.66
B		0.07	0.14	B		0.07	0.24
C		0.17	0.21	C		0.17	0.29
D		0.50	0.50	D		0.50	0.58
A	0.55	0.62	0.68	A	0.45	0.62	0.62
B		0.07	0.27	B		0.07	0.14
C		0.17	0.33	C		0.17	0.21
D		0.50	0.62	D		0.50	0.50
A	0.46	0.62	0.63	A	0.53	0.62	0.67
B		0.07	0.16	B		0.07	0.26
C		0.17	0.23	C		0.17	0.31
D		0.50	0.52	D		0.50	0.60
A	0.50	0.62	0.66	A	0.50	0.62	0.66
B		0.07	0.24	B		0.07	0.24
C		0.17	0.29	C		0.17	0.29
D		0.50	0.58	D		0.50	0.57
A	0.60	0.62	0.73	A	0.55	0.62	0.68
B		0.07	0.30	B		0.07	0.27
C		0.17	0.37	C		0.17	0.33
D		0.50	0.68	D		0.50	0.62

Source: authors

out. The results show that this system can assess navigational collision risk effectively. Considering the situations around Korean coastal sea, the simulation to validate the designed system is implemented. The vulnerability increases as the traffic conditions and environment become worse. The simulation reflected the vulnerability affects the basic collision risk and the consideration of vulnerability can help alert navigators about navigational collision risk to reduce the number of collision accidents. Further, investigations are suggested to identify factors and coefficients for thorough calculations for the issues of vessel collision involving non-SOLAS ships. The gained results can give a general recommendation for solving collision risk at coastal sea.

Finally, future work should address more variables of vulnerability factors which can be clustered according to different environmental conditions for various vessels including SOLAS and non-SOLAS ships and the optimization work using advanced AHP method will be done for providing an accurate and detailed results of collision risk detection. Based on the navigational collision risk, the path planning algorithm will be conducted for a complete collision avoidance system.

Acknowledgment

This research is a part of the project titled “SMART-Navigation project,” funded by the Ministry of Oceans and Fisheries, the National Natural Science Foundation of China (61873071, 51911540478, G61773015), key research and development plan of Shandong province (2019JZZY020712), Natural Science Foundation of Shandong Jiaotong University [Z201631], Shandong Jiaotong University PhD Startup foundation of Scientific Research.

References

Ahn, J.H., Rhee, K.P., You, Y.J., 2012. A study on the collision avoidance of a ship using neural networks and fuzzy logic. Appl. Ocean Res. 37, 162–173.

An, K., 2016. E-navigation services for non-SOLAS ships. Int. J. e-Navig. Mari. Econ. 4, 13–22.

Asbjornslett, B.E., 1999. Assess the vulnerability of your production system. Prod. Plann. Contr. 10 (3), 219–229.

Do, T.M.H., Park, G.K., Hong, T.H., Kim, G., 2018. A study on the structure analysis of vulnerability factors of marine accident to coastal cargo ships using FSM. J. Korean Instit. Intell. Syst. 28 (6), 589–594.

Emrah, B., Okan, D., Tuba, K., ShigeruY, 2012. Use of consistency index, expert prioritization and direct numerical inputs for generic fuzzy-AHP modeling: a process model for shipping asset management. Expert Syst. Appl. 39 (2), 1911–1923.

Fang, M.C., Tsai, K.Y., Fang, C.C., 2018. A simplified simulation model of ship navigation for safety and collision avoidance in heavy traffic areas. J. Navig. 71 (4), 837–860.

Hasegawa, K., 1987. Automatic collision avoidance system for ships using fuzzy control. In: Proceedings of the 8th Ship Control System Symposium.

Hasegawa, K., Kouzuki, A., Muramatsu, T., Komine, H., Watabe, Y., 1989. Ship auto navigation fuzzy expert system (SAFES). J. Soc. Nav. Archit. Jpn. 166.

House, D., 2007. Ship Handling. Routledge.

Hwang, C.N., 2002. The integrated design of fuzzy collision-avoidance and H∞-autopilots on ships[J]. J. Navig. 55 (1), 117–136.

John, A., Osue, U.J., 2017. Collision risk modelling of supply vessels and offshore platforms under uncertainty. J. Navig. 70 (4), 870–886.

Kao, S.L., Lee, K.T., Chang, K.Y., Ko, M.D., 2007. A fuzzy logic method for collision avoidance in vessel traffic service. J. Navig. 60 (1), 17–31.

Korea Hydrographic and Oceanographic Administration (KHOA), 2013. Ocean Observa-Tion and Prediction. http://khoa.ko.kr/.

Kim, G.N., 2017. Survey on the Korean VMSs for Fishing Vessels and Challenges for Monitoring the High-Risk Ships. SMART Navigation Project, e-Navigation Underway 2017 AP.

Kim, D.B., Jeong, J.Y., Park, Y.S., 2014. A study on the ship's speed control and ship handling at Myeongnayang waterway. J. Korean Soc. Mar. Environ. Saf. 20 (2), 193–201.

Korean Marine Security Safety Division, 2016. Statistical Yearbook of Marine Accident Incident.

Korean Marine Security Safety Division, 2017. Statistical Yearbook of Marine Accident Incident.

Lee, H.J., Rhee, K.P., 2001. Development of collision avoidance system by using expert system and search algorithm. Int. Shipbuild. Prog. 48 (3), 197–212.

Lee, S.M., Kwon, K.Y., Joh, J., 2004. A fuzzy logic for autonomous navigation of marine vehicles satisfying COLREG guidelines. Int. J. Contr. Autom. Syst. 2 (2), 171–181.

Lisowski, J., 2001. Determining the optimal ship trajectory in collision situation. In: Proceedings of the IX International Scientific and Technical Conference on Marine Traffic Engineering. Szczecin.

Ministry of Oceans and Fisheries, 2016. Republic of Korea. SMART-Navigation Project. http://www.smartnav.org/eng/html/Index/.

Mou, J.M., Van, D., Tak, C., Ligteringen, H., 2010. Study on collision avoidance in busy waterways by using AIS data. Ocean Eng. 37 (5–6), 483–490.

Sahin, B., Senol, Y.E., 2015. A novel process model for marine accident analysis by using generic fuzzy-AHP algorithm. J. Navig. 68 (1), 162–183.

Sahin, B., Senol, Y.E., 2017. Shipping technology selection for dynamic capability based on improved Gaussian fuzzy AHP model. Ocean Eng. 136 (15), 233–242.

Szlapczynski, R., 2006. A unified measure of collision risk derived from the concept of a ship domain. J. Navig. 59, 477–490.

Zhou, D., Zheng, Z., 2019. Dynamic fuzzy ship domain considering the factors of own ship and other ships. J. Navig. 72 (2), 467–482.

Yancai Hu, Received the Ph.D degree from Mokpo National Maritime University, Interested fields: Fuzzy control, Collision risk analysis, Nonlinear adaptive control Phone: +82–01033752388 E-mail: yancaihu@126.com

Gyei-Kark Park, Received the Ph.D degree from Tokyo Institute of Technology, Interested fields: Fuzzy, Game theory and International logistics., Now: Professor in Mokpo National Maritime University, Phone: +82–01032072344, E-mail: gkpark@mmu.ac.kr