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FUZZY GROUNDING ALERT SYSTEM FOR VESSEL TRAFFIC SERVICE VIA 3D MARINE GIS

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Key words: grounding alert, marine GIS, fuzzy logic control, danger alert angle, vessel traffic service.

ABSTRACT

There have been intensive discussions about methods to prevent vessels from grounding when sailing near offshore or harbor areas because grounding accidents always cause oil pollution around coastline areas. This study used a marine geographic information system (MGIS) to survey the 3D seabed topography and geology in order to build a novel virtual aid for navigation with a grounding alert. Dynamic and static data were provided by using the Automatic Identification System (AIS) as the input, and fuzzy logic control was used for computation of the output. The maximum draft point along the vessel's route was configured as a reference point, and a swath angle of 0°-90° was used to search the seabed topography segments and obtain the Water Depth Swath Angle (WDSA) based on the concept of the compression and dilation equations for time and space. The MGIS was used as the data processing platform. After analysing the professional sailing rule base with the high alert rule base with regard to the security benefit of the hazard alert, an appropriate alert distance was configured. Moreover, AIS/MGIS could be used for XTE (cross track error) calibration. Based on three alert levels (amber, red, and flashing red/alarm), VTS operators and crewmembers can obtain precise alerts to perform effective avoidance before vessels enter shallow water.

I. INTRODUCTION

Vessels that are sailing near shore can be involved in marine accidents including collisions and groundings due to human errors. These accidents can result in casualties, financial damage, and oil spills. Leaks in large oil or chemical tankers are often the most serious because these directly damage the environment and pose a great threat to coastal survival and development. Often, when vessels are in danger of collision, avoidance information is provided by an Automatic Radar Plotting Aid (ARPA), including the Closest Point of Approach (CPA), Time of Closest Point of Approach (TCPA), or other relevant information about other vessels. These data are provided to the officer of the watch (OOW) so that they can develop strategies and act to prevent collisions. The focus of this paper is a method to avoid the grounding hazards that arise from unfamiliar underwater topography near an offshore or harbor area. This is especially important if a vessel is sailing in an area for the first time, and the local hydrological environment is unfamiliar.

This topic is one of the most important issues faced by Vessel Traffic Services (VTS), and is the focus of the present study.

In the past, a collision avoidance method using radar images was presented (Hayashi et al., 1991). An automatic collision avoidance method using Electronic Chart Display and Information Systems (ECDIS) when navigating in restricted water was also proposed (Yang et al., 2006). A collision avoidance system integrated with ECDIS and AIS was demonstrated to increase navigation safety (Pillich and Buttgenbach, 2001). However, it was still unable to detect the danger level caused by an unfamiliar underwater 3D topography and provide early warning indications. More recently, a two-stage alert architecture was proposed for ship grounding prediction in a VTS (Yang et al., 2011). A geometry model has also been proposed for ship grounding prediction, and a hazard area was established for a grounding risk index (GRI) based on fuzzy theory calculations (Yang et al., 2012). Currently, ECDIS functions can provide the OOW with knowledge about the bathymetric depth below a vessel and indicate the maneuverability and draft of a ship sailing in a VTS area, but these are unable to deliver underwater 3D high resolution terrain data around the navigation route with advance alerts.

In this study, a virtual navigation simulator was proposed with a grounding alert to improve the limitations of current navigation instruments. The most significant achievements in the 3D research area concerning key issues of 3D GIS, i.e., 3D structuring and 3D topology, are summarized to portray the current research status (Zlatanova et al., 2002). At the present time, there is no single cost-effective alert system that focuses on the

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local 3D hydrological topography for VTS. None of the systems have alert functions or mechanisms that provide danger levels after analyzing and judging a grounding problem. A simple method for the rapid assessment of ship bottom structures subjected to grounding over seabed obstructions with large contact surfaces is proposed (Hong and Amdahl, 2012). In addition, an intelligent collision avoidance system (Perera et al., 2011; Campbell et al., 2012) and AIS-based collision avoidance (Mou et al., 2010) are proposed for navigation.

To effectively solve the practical problem described above, and to enhance the on-shore capability to prevent grounding, this study used dynamic and static data provided by AIS, together with a Marine Geographic Information System (MGIS) and fuzzy control algorithm, to develop a novel Vessel Grounding Alert (VGA) model. Through the use of a VGA fuzzy control model combined with the VTS application of fuzzy logic collision avoidance proposed previously (Kao et al., 2007), VTS monitoring staff can give an immediate warning and guidance based on the MGIS calculated alert. First, for the navigation route of a vessel with grounding risks, the corresponding cross-sectional view of the seabed and alert information are compiled and used as the fundamental basis to trigger the VGA. An interactive correspondence analysis is performed on the location points along the route and the rule base. The results and Water Depth Swath Angle (WDSA) are used as the reference to measure the degree of risk during the time of alert. This helps the personnel on shore and the monitoring personnel on board to provide different hazard warning levels as the vessel gradually sails into hazardous areas. Finally, a high warning fuzzy rule base is constructed to compare the efficiency during each stage of warning, and risk indicators are calculated. It is hoped that by using the VGA designed in this study, a novel warning indicator for grounding can be provided. Most ECDISs have a look ahead function (user definable and with variable width-normally a cone) and provide advance grounding warnings, However, this look ahead function is not appropriate for near-shore navigation and heavy traffic navigation in VTS surveillance areas (an ECDIS will easily give an alarm in a VTS area). Many ECDIS functions are unable to work smoothly in a port, or near the coast. An ECDIS does not have high-resolution 3D seabed information for near shore areas to avoid grounding. For example, on March 10, 2016, the T. S. Line drifted off course as a result of losing power after leaving Keelung port. The stranded ship caused an oil spill and coastline oil pollution. Hence, VTS operators with VGA (vessel grounding alert and 3D underwater contour) systems should have a function to alert the Captain to avoid an accident when the ship drifts from her planned route using VHF Channel 16. This grounding alert system is a decision-making mechanism for VTS operators to maintain navigation safety. The high-quality 3D topology data are obtained by hydrographic harbor surveys to provide details of the underwater 3D high-resolution contours. However, it may not be able to provide a universal service without sufficient high-resolution survey data.

II. RESEARCH METHODS AND PROCEDURES

The VGA model is used to calculate the three warning triggering points along the route for individual vessels, and is constructed based on three procedures:

Step 1. Data conversion chart. By converting chart data, electronic chart data is digitised and interpolated. A continuous grid layer is generated and used as the operating layer for the VGA model.

Step 2. Warning indicator definitions. Standards for ship manoeuvrability are used for configuring the alert distance. By generating a continuous grid layer, each location point along the route contains 3D data and can be used to calculate the water depth swath angle.

Step 3. Fuzzy logic control. The VGA model uses fuzzy logic control. Based on current navigation conditions and different seabed topography and geology, corresponding warnings for different locations along the route can be determined. Navigation and hydrographical information provided by AIS (e.g., ship speed and sea conditions-from the government weather report center providing the hydrological data broadcasting system) are used as input linguistic variables for fuzzy logic control.

Different fuzzy expert rules and high alert rules are used to calculate and output the WDSA. The actual proportion specifications are then restored and the most suitable warning distances are obtained. Along the navigation route, three levels of warnings are displayed for a warning position (amber, red and flashing red/alarm).

1. Data Conversion Chart

Before the construction of the VGA model, a mesh terrain surface using interpolation must first be constructed with the following steps:

Spatial data editing (or digitization) is performed on the existing depth points. First, depth point data sets are prepared in the GIS database from the near shore hydrographic survey project. This allows the system to precisely confirm the depth of each depth point following the specification by the IHO standard (IHO, 2008). If the port authority already has high precision 3D depth information in an electronic txt or xml file containing longitude, latitude, and depth data, the digitization process can be omitted. Data (x, y, z) can then be imported to construct the point layer.

2. Warning indicator Definitions

Hayashi et al. (1991) proposed the division of 120° circular sectors into four alert regions using four different radii configured by crew members. The alert distance used in the VGA model is configured based on ship manoeuvrability. Upon activation of the alert system, searches are performed for the shallow water avoidance boundary positions (positions where the ship could be grounded) along the route. In other words, before the ship sails to the final alert position, the shallow water position can still be avoided by using full rudder.

Resolution IMO MSC.137 (76) (IMO, 2002) states that ships must be constructed in accordance with the standards listed in the resolution. Related standards for manoeuvrability are: turning advance: the advance should not exceed 4.5 ship lengths; crash astern stopping distance: the track reach in the full astern shipping test should not exceed 15 ship lengths.

In the VGA Model, there are two basic alert occasions. One is when the shallow water point is 15 ship lengths away, and the other is when the shallow water point is 4.5 ship lengths away. The alert distance depends on different ship lengths. The VGA model contains five components and the definitions and function descriptions are listed below.

1) Searching Line Segment

Based on the current location of the vessel, 15 times the ship length in the direction of sail is taken and used as the distance for a searching the line segment for a shallow water point.

2) Shallow Water Point (SWP)

Search for the closest SWP on the searching line segment and set it as the trigger for warnings. When the vessel is sailing in the water where the ratio of depth (H)/draft (d) is less than two, the initial turning advance is dramatically increased and the manoeuvrability is decreased. This study defines as the location only for near-shore shallow waters; otherwise, the value is too high for large vessels in port or off-shore. Within the searched area, the point that lies on the searching line segment and is the closest to the vessel is regarded as the SWP.

3) First Alert Point (AP1)

According to the IMO standard for crash astern stopping distance (IMO, 2002), if a SWP is triggered at a position along the route and within 15 ship lengths, the first alert point (AP1) on the navigation route is generated. This study found that the use of full astern and full rudder are not good choices for navigation. Usually, the OOW will use a small amount of rudder early rather than using full astern or full rudder at the last possible moment.

4) Final Alert Point (AP3)

According to IMO standard for turning advance, if a SWP is triggered at a position along the route and within 4.5 ship lengths, and in the presence of AP1, this is defined as the final alert point (AP3). During an emergency situation, the ship can only use full rudder to prevent a grounding incident. At the same time, the ship has to prevent the rudder from losing its function in shallow water areas. If all emergency actions have been taken but fail, then the OOW can only attempt to do his best by using full astern and rudder hard over to minimize damage.

5) Fuzzy Alert Point (AP2)

Before the final alert point, an OOW or VTS monitoring personnel must be continuously provided with effective early avoidance measures during the warning period. To prevent human errors, in the actual fuzzy logic algorithms, as the vessel speed increases (especially when it is greater than 20 knots), the distance to the hazardous water with grounding risk is compressed and reduced. During the calculation using fuzzy theory, the angular difference between each WDSA at different danger levels is not very large. WDSA from the fuzzy control output are selected for the present study. First, the compression ratio must be defined based on the ship speed and magnitude of the gradient of the undersea terrain. After compression, each danger warning point is defined using fuzzy logic control. Based on the danger level, a point is defined along the navigation route. The values should be between AP1 and AP3. This point is a result of current navigation conditions, seabed topography, and geology. It is more suitable to meet the operational requirements for collision avoidance. Examples of AP1, AP3, and AP2 are shown in Fig. 1 as part of the VGA model process flow.

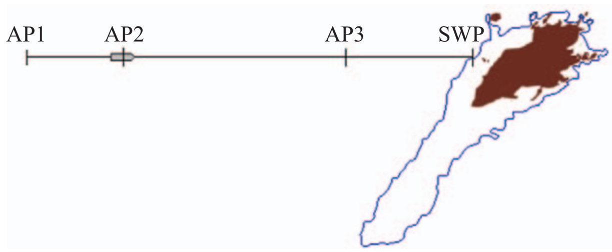


Fig. 1. VGA Model operation.

The following case is considered. A ship is west of Keelung Islet, heading 090. The ship length is 150 metres and the draft is 5 metres. The searching line segment is moving forward with the vessel's direction of movement (not only vessel's heading). During the searching process, a SWP with water depth less than 10 m is found and the alert system is activated. AP1 and AP3 are generated along the navigation route, 15 ship lengths and 4.5 ship lengths away, respectively. Based on the current navigation conditions and underwater terrain, the corresponding AP2 is found along the searching line segment. If the ship continues to sail and reaches AP2 defined by the system, an alert action must be performed.

3. Define WDSA

The chart data is converted into continuous grid layers, the spatial data for any given point contains latitude, longitude, and depth expressed in (x, y, z) coordinates. A cross-sectional view of the seabed topography along the mobile navigation route is obtained and the interpolation algorithm uses the universal Kriging interpolation method. The effect of seabed topography and geology on ship groundings is evaluated. WDSA (0°-90° with one degree increment) is used to describe the underwater terrain around the hazardous area, and the WDSA will be changed depending on the sea bottom topography uncertainty. Along the navigation route, the deepest draft is used as the basic point to perform 3D underwater terrain rendering, as shown in Figs. 2(a)-(c) show the corresponding location and angle along the navigation route for

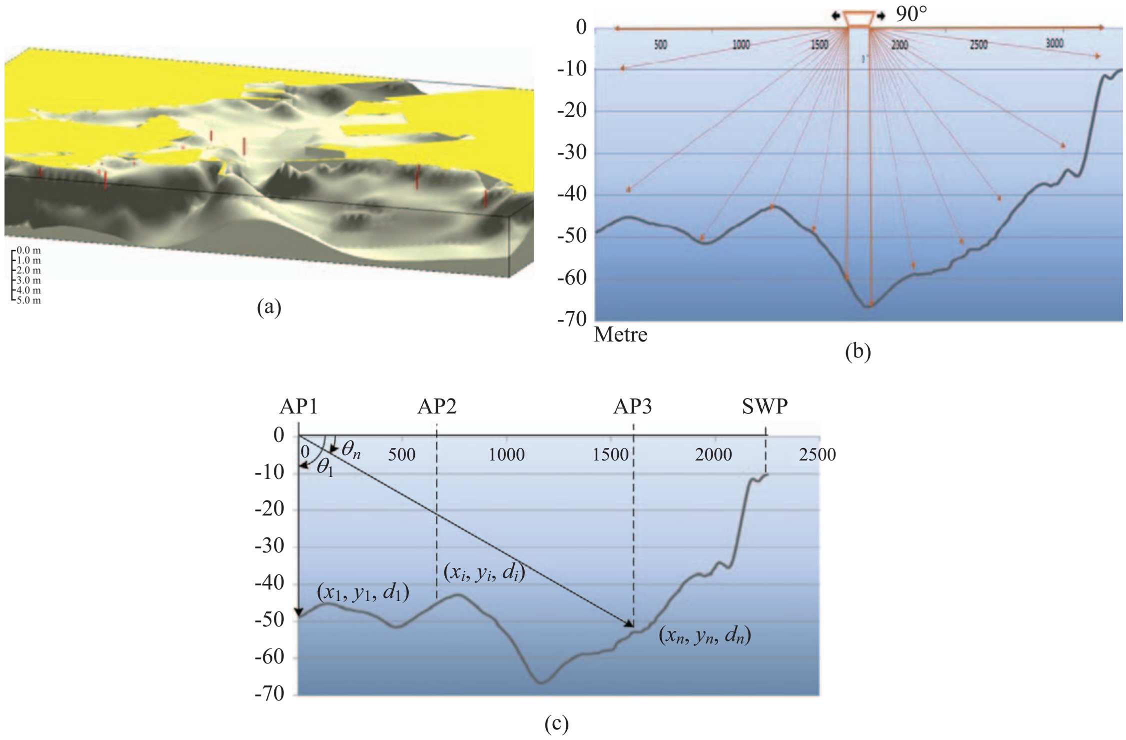


Fig. 2. (a) The 3D underwater terrain in Keelung Harbor by survey; (b) WDSA, using 0°~90° to search depth of seabed; and (c) Fuzzy WDSA depth calculation.

AP2 based on fuzzy control. Each point contains 3D data and can generate a corresponding angle to AP1. This is defined as the WDSA. AP2 is between AP1 and AP3. Suppose the coordinate for AP1 is (x_1, y_1, d_1), and AP3 is (x_n, y_n, d_n), then the effective angle range is between 90° and, as shown in Fig. 2(b). WDSA for each location are calculated as below:

$$\ell_i \approx \sqrt{(x_i - x_1)^2 + (y_i - y_1)^2},\ i = 1 - n$$

$$\text{Therefore } \theta_i = \tan^{-1}\left(\frac{d_i}{\ell_i}\right) \tag{1}$$

The area for WDSA is limited to AP3, and the distance between AP1 and AP3 is 10.5 ship lengths (10.5 L); the corresponding angle for AP3, θ_n is

$$\ell_i \approx \sqrt{(x_i - x_1)^2 + (y_n - y_1)^2}, 10.5\ L$$

$$\text{Therefore } \theta_n = \tan^{-1}\left(\frac{d_n}{10.5\ L}\right) \tag{2}$$

where (x_i, y_i) is the latitude and longitude for each alert point between AP1 and AP3, and d_i is the depth

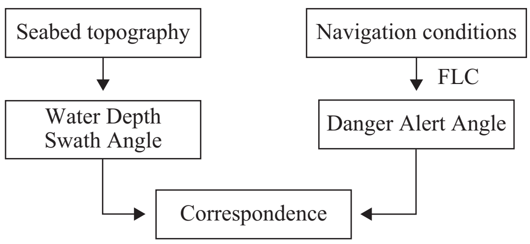


Fig. 3. Corresponding danger alert angle.

4. Selection of WDSA in Fuzzy Logic Control

When designing the VGA Model, monitoring personnel onshore who are giving warnings based on navigation conditions of the vessels within the monitoring area were considered. The size of the WDSA is proportional to the danger level. A larger angle means a shorter alerting distance on the navigation route, and it means personnel onshore must provide immediate warning to the vessels. Based on navigation conditions, fuzzy logic control system outputs an angle, known as the Danger Alert Angle (DAA). Each point on the seabed topography along the navigation route can form WDSA with AP1. The warning distance can be obtained through the corresponding DAA, as shown in Fig. 3.

A simple bisection method cannot be used solely for determining DAA since there are many other influencing factors and properties such as the expected grounding location, ship speed, sea conditions, seabed topology, and seabed slop. Fuzzy Logic

Table 1. Return interval for shipborne mobile devices in class A vessels.

Ship manoeuvre condition	Standard return interval
At anchor or mooring and moving slower than 3 knots	3 min
At anchor or mooring and moving faster than 3 knots	10 sec
Sailing 0 -14 knots	10 sec
Sailing 0-14 knots while changing direction	3.33 sec
Sailing 14-23 knots	6 sec
Sailing 14-23 knots while changing direction	2 sec
Sailing over 23 knots	2 sec
Sailing over 23 knots while changing direction	2 sec

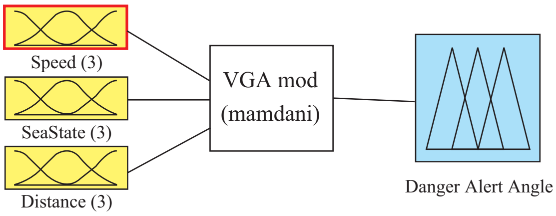


Fig. 4. Fuzzy control system diagrams.

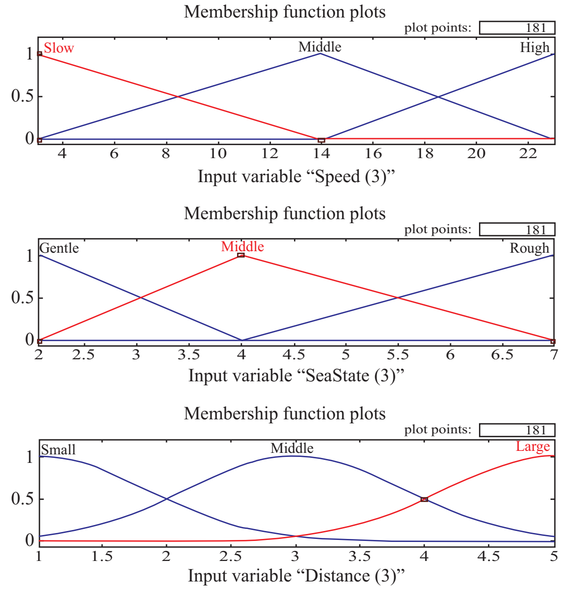


Fig. 5. Linguistic set for linguistic variables. (a) Speed: slow (S), medium (M), and fast (F); (b) Sea-state (sea conditions) gentle (G), medium (M), and rough (R); and (c) Distance: small (S), medium (M), and large (L).

Control (FLC) can be used. Based on given input values, many influences can be eliminated. These influences can be from different human perceptions or uncertainties due to environmental variables.

1) System Architecture for Fuzzy Logic Control

The fuzzy system can contain four principal elements including fuzzification, fuzzy rule base, fuzzy inference engine and defuzzification (Kao et al., 2007).

2) Define the Linguistic Variable

Taking safety into consideration, three linguistic variables are used as the input: ship speed, sea conditions, and distance. For ship speed and sea conditions, trigonometry can be used to present the linguistic variables. An experienced captain is better at controlling distance and operating ships. The peak characteristic of trigonometric functions is not significantly shown and it is considered to be closer to a Gaussian distribution. Distance is therefore represented by Gaussian functions as the input linguistic variable. The output is a trigonometric function of linguistic variables for the DAA as shown in Fig. 4. Each linguistic variable is defined below.

(1) Speed

It has three membership functions: slow, middle and fast. The velocity is configured by referencing AIS standards on transmission intervals for class A.

Table 1 shows the return interval for shipborne mobile devices. The fuzzy internal points 3, 14, and 23 follow the return interval for shipborn mobile devices in class A vessels as shown. The ship maneuver conditions of AIS are 3, 14, and 23 knots for 3 min, 10 s, and 2 s, respectively.

Based on the basic concept that ship speed is proportional to radio transmission frequency, a ship speed of 14 knots is configured to be the median value between slow and fast ship speeds. The linguistic set is shown in Fig. 5(a). Table 2 shows the sea conditions.

Speed in the VGA model is defined as:

μ_{slow}: Suppose the ship speed is close to 3 knots, the membership function is $\mu_{slow}(x)$

μ_{middle}: Suppose the ship speed is close to 14 knots, the membership function is $\mu_{middle}(x)$

μ_{fast}: Suppose the ship speed is close to 23 knots, the membership function is $\mu_{fast}(x)$

$$\mu_{slow}(x) = \begin{cases} 1 & for \quad x \le 3 \\ \dfrac{14-x}{11} & for \quad 3 \le x \le 14 \end{cases} \tag{3}$$

Table 2. International classifications for sea conditions.

Sea condition levels	Sea condition	Wave range (metre)
0	Calm-glassy	0
1	Calm-rippled	0-0.1
2	Smooth-wavelet	0.1-0.5
3	Slight	0.5-1.25
4	Moderate	1.25-2.50
5	Rough	2.50-4.0
6	Very rough	4-6
7	High	6-9
8	Very high	9-14
9	Phenomenal	>14

$$\mu_{middle}(x) = \begin{cases} \dfrac{x-3}{11} & for \quad 3 \le x \le 14 \\ \dfrac{23-x}{9} & for \quad 14 \le x \le 23 \end{cases} \tag{4}$$

$$\mu_{fast}(x) = \begin{cases} \dfrac{x-14}{9} & for \quad 14 \le x \le 23 \\ 1 & for \quad 23 \le x \end{cases} \tag{5}$$

(2) Sea-state

This has three membership functions: gentle, medium, and rough. Table 2 in the International classification for sea conditions by the World Meteorological Organization (WMO) is used to define the linguistic variable, ranging from level 2 to level 7. Level 7 is therefore the upper limit and the linguistic set is shown in Fig. 5(b). The fuzzy internal points 2, 4, and 7 follow the Keelung harbor weather report long term calculations (by N.T.O.U.), where 2 is the smallest, 4 is moderate, and 7 is the highest limit level (> 7 Harbor will be closed).

Sea-state is defined in the VGA Model as:

μ_{gentle}: Suppose the sea condition is close to level 2, the membership function is $\mu_{gentle}(y)$

μ_{medium}: Suppose the sea condition is close to level 4, the membership function is $\mu_{medium}(y)$

μ_{rough}: Suppose the sea condition is close to level 7, the membership function is $\mu_{rough}(y)$

$$\mu_{gentle}(y) = \begin{cases} 1 & for \quad y \le 2 \\ \dfrac{x-14}{9} & for \quad 2 \le y \le 4 \end{cases} \tag{6}$$

$$\mu_{medium}(y) = \begin{cases} \dfrac{y-2}{2} & for \quad 2 \le y \le 4 \\ \dfrac{7-y}{3} & for \quad 4 \le y \le 7 \end{cases} \tag{7}$$

$$\mu_{rough}(y) = \begin{cases} \dfrac{y-4}{3} & for \quad 4 \le y \le 7 \\ 1 & for \quad 7 \le y \end{cases} \tag{8}$$

(3) Distance

The present study focuses on the crash astern stopping distances for different vessels. A survey has been conducted to investigate the crash astern stopping distance required for navigation equipment when the vessel is encountering obstacles. Three membership functions for the required distance are defined. According to linguistic variables, they are: small, medium, and large. The membership functions are Gaussian functions and the linguistic set is shown in Fig. 5(c).

$$\mu_{small}(z, 1, 2, 2) = \left\{ \exp\left[-\frac{1}{2} \left| \frac{z-1}{2} \right|^2 \right] \right. \tag{9}$$

$$\mu_{medium}(z, 3, 2, 2) = \left\{ \exp\left[-\frac{1}{2} \left| \frac{z-3}{2} \right|^2 \right] \right. \tag{10}$$

$$\mu_{large}(z, 5, 2, 2) = \left\{ \exp\left[-\frac{1}{2} \left| \frac{z-5}{2} \right|^2 \right] \right. \tag{11}$$

(4) Parameter DAA

The three DAA membership functions are: small, medium, and large, ranging between 90° and θ_n. To solve the DAA in fuzzy logic control, it can be treated as an output for danger levels. The present study defines variable for DAA as follows:

μ_{smell}: When the parameter is close to θ_n, the membership function is $\mu_{smell}(z)$

μ_{medium}: When the parameter is close to 45° + 0.5 θ_n the membership function is $\mu_{medium}(z)$

μ_{large}: When the parameter is close to 90° the membership function is $\mu_{large}(z)$

$$Suppose\ \theta_n = \tan^{-1}\left(\frac{d_n}{10.5\ L}\right)$$

$$\mu_{small}(z) = \begin{cases} 1 & for \quad z \le \theta_n \\ \dfrac{45° + 0.5\theta_n - z}{45° - 0.5\theta_n} & for \quad \theta_n \le z \le 45° + 0.5\theta_n \end{cases} \tag{12}$$

$$\mu_{medium}(z) = \begin{cases} \dfrac{z-\theta_n}{45° - 0.5\theta_n} & for \quad \theta_n \le z \le 45° + 0.5\theta_n \\ \dfrac{90° - z}{45° - 0.5\theta_n} & for \quad 45° + 0.5\theta_n \le z \le 90° \end{cases} \tag{13}$$

Table 3. Experts rule base.

Rules	Speed	Sea Conditions	Distance	DAA
R1	S	G	S	S
R2	S	M	S	S
R3	S	R	M	M
R4	M	G	S	S
R5	M	M	M	M
R6	M	R	L	L
R7	F	G	M	M
R8	F	M	L	L
R9	F	R	L	L

Table 4. High alert rule base.

Rules	Speed	Sea Conditions	Distance	DAA
R1	S	G	S	S
R2	S	M	M	M
R3	S	R	L	L
R4	M	G	M	M
R5	M	M	M	M
R6	M	R	L	L
R7	F	G	M	M
R8	F	M	L	L
R9	F	R	L	L

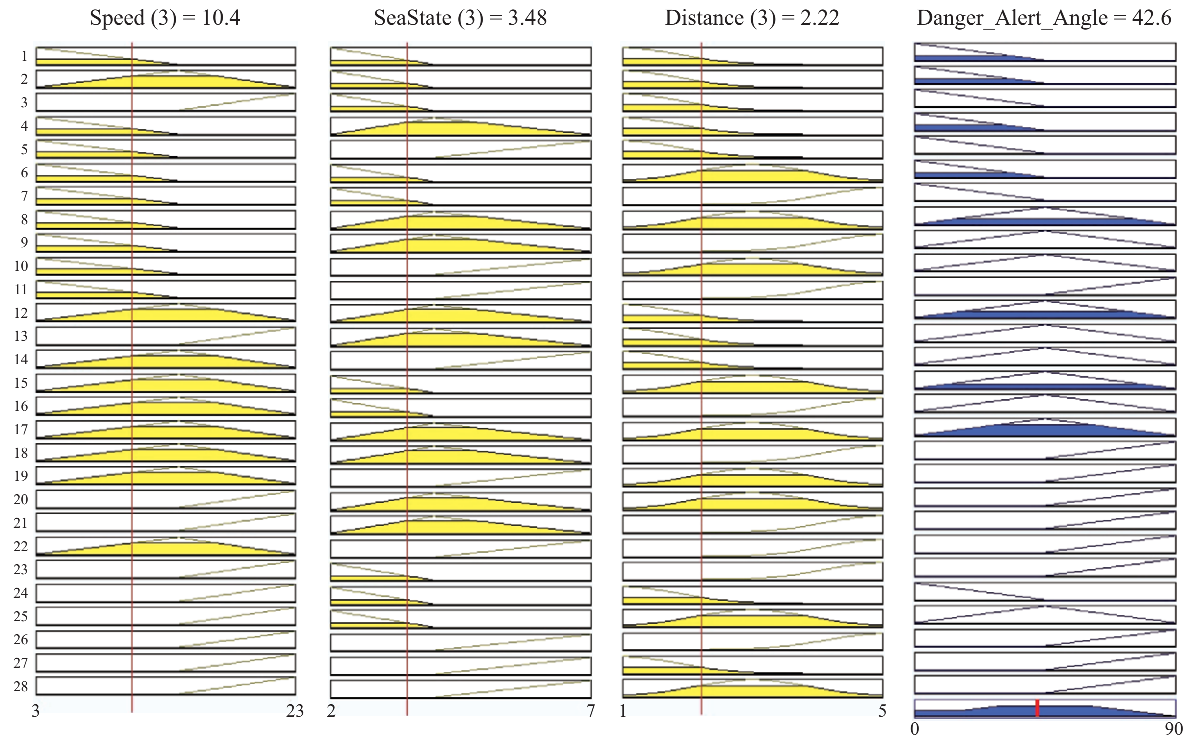


Fig. 6. Fuzzy algorithm.

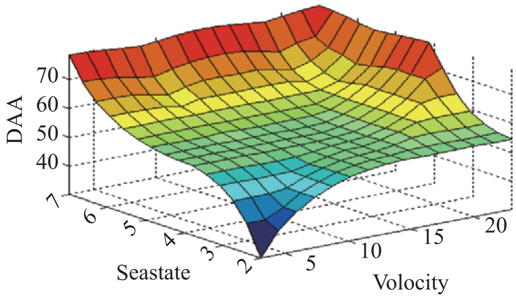


Fig. 7. Control curves for the high alert rule bases.

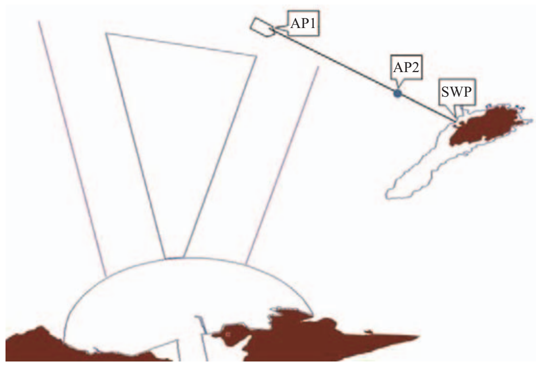


Fig. 8. Ship location diagram.

$$\mu_{large}(z) = \begin{cases} \dfrac{z - 45° - 0.5\theta_n}{45° - 0.5\theta_n} & for \quad 45° + 0.5\theta_n \le z \le 90° \\ 1 & for \quad 90° \le z \end{cases} \tag{14}$$

3) Construct Rule Base

This is to describe human control behaviour. In fuzzy logic control, rules are constructed by series of "if/then" statements. Generally, "if" is the first part and "then" follows. It can be expressed as:

If (Velocity is fast) and (Sea state is rough) then (Danger Angle is large)

Two rule bases were proposed, and their effectiveness under expert rule base and high alert conditions were compared. Both rule bases used the top 9 ranking rules by more than 35 captains and VTS experts, as shown in Tables 3 and 4.

4) Fuzzy Algorithm for DAA

When the data are continuous, the center of gravity method is often used. The fuzzy solver can be derived by MATLAB, as shown in Fig. 6. The membership function curve and the abscissa are used to mark the center of the focus in the area. This is the final output value. The control curves for a high alert rule base are shown in Fig. 7. During the control process, users emphasize on the effect of sea conditions. When the sea conditions are rough, this changes the linguistic variable Speed, and does not have a large effect on the output DAA; this is mostly concentrated in a large angle with a high alert situation.

III. EXPERIMENTS

The DAA is not like the ones in an ordinary alert model. Instead of being limited to 2D, 3D is used. Along the navigation route, DAA is used to define the corresponding warning distance under the influence of different terrain situations. The warning distance corresponds to WDSA, and does not only rely on defining a fixed distance. Two experiments are performed in the present study. They are used to investigate if the corresponding warning distance agrees with the actual control requirements in the event where an alert has been triggered. First, experiment 1 analyses the corresponding distance before and after the VGA model performs spatial compression. Experiment 2 compares the warning efficiencies for an expert rule base and a high alert rule base when the navigation conditions are the same. In experiment 1, the sea condition is set to be level 2 (Smooth-Wavelet) with the corresponding DAA. The WDSA and the corresponding distances are obtained. In experiment 2, the sea condition is set to be level 5. In the ship-handling simulator, turning operations of different angles are performed to simulate the avoidance of shallow water.

1. Warning Distance

The DAA constructed must confirm the location of AP2 by performing searches based on the correspondence table for WDSA. Simulated vessel #1 from the National Taiwan Ocean University is used in the experiment, with the following data:

Experiment 1 Name：
vessel #1 Model: 630 TEU container ship
Length: 151.6 m
Width: 23.5 m
Heading: 123°
Draft: 5 m
AP1 location: 121°45'45.396"E 25°12'19.465"N
Input system variables: speed 15 knots, sea condition level 2

In Fig. 8, the searching line segment for vessel 1 has triggered the shallow water point. The effects of the draft, dynamic draft, squat, and water levels were considered using the ship handling simulator in N.T.O.U. Using 15 ship lengths and 4.5 ship lengths, AP1 and AP3 are generated. In this figure, it can be seen that if the vessel continues to head on 123° then it will ground. After generating AP1 and AP3, the system generates AP2 based on sailing conditions and changes in seabed.

The steps are as follows:

1. Extract data from the cross-sectional view of the navigation route and find correspondence between AP1 and all underwater points between AP1 and AP3. A correspondence table for WDSA is generated, as shown in Table 5.
2. A ship speed of 15 knots and level 2 sea conditions were used as the control input for the fuzzy system. An expert rule

Table 5. WDSA results in experiment 1.

ID	Distance (m)	Depth (m)	WDSA	ID
AP1(1)	0	75.3	0.00	AP1(1)
…	…	…	…	…
5	52	75.3	55.37	5
6	***65***	***75.3***	***49.20***	***6***
…	…	…	…	…
AP3(128)	1587	58.8	2.12	AP3(128)

Table 6. AP2 values from experiment 1 after compression.

ID	Original Distance (m)	Distance after compression (m)	Depth (m)	WDSA
AP1(1)	0	0	75.3	0
2	15	1.5	75.3	88.86
…	…	…	…	…
40	***489***	***48.9***	***76.2***	***57.31***
…	…	…	…	…
AP3(128)	1587	158.7	58.8	20.33

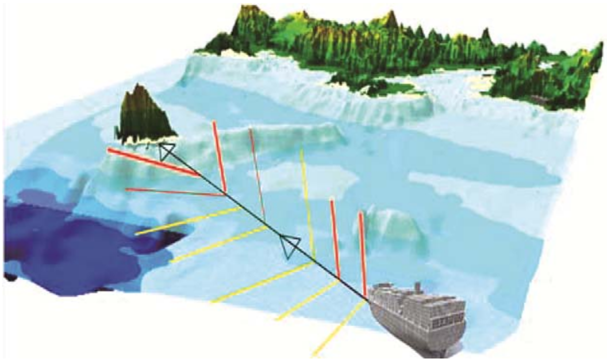
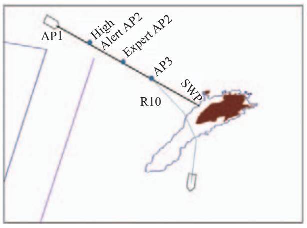
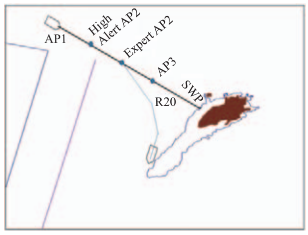


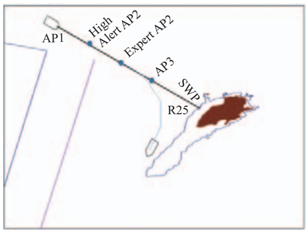
Fig. 9. Coast of Keelung harbor, 3D diagram for SWP.



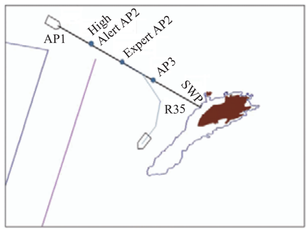
(a) Right Rudder 10°



(b) Right Rudder 20°



(c) Right Rudder 25°



(d) Right Rudder 35°

Fig. 10. Avoidance diagram for each rudder angle.

base is used to perform the fuzzy solver before performing spatial compression. The DAA obtained is 48.7°.

3. Using 48.7° as the search target, all of the fields in Table 5 are searched. Table 5 contains WDSA. The closest angle is 49.2°. On the navigation route, the warning distance for this angle is 65 m. This means that after the initial alert trigger at AP1, the location for AP2 is 65 m later. When converted to WDSA, each WDSA is significantly increased after compression. Using a compression ratio of 10, as listed in Table 6, the WDSAs are used to generate AP2. After compression, the warning distance is improved to 489 meters.

Taking vessels on the coast of Keelung harbor as samples, Fig. 9 shows the 3D diagram for SWP locations in surrounding areas along the navigation route, which were calculated in experiment 1. The estimated navigation point is first calculated. Each arrow represents the sailing position after every 6 min. Based on the GIS seabed topography (Zlatanova et al., 2002), and following the ESRI ArcGIS 3D spatial analysis module free trial (ESRI), we implemented the Keelung port VTS project "Establishment of the Keelung port 3D Marine GIS." To obtain the high resolution 3D seabed topography and geology in 2001 and 2002, hydrographic survey procedures were followed using a multi-beam Submetrix ISIS 100Swath Bathymetry system for the Keelung harbor area only. The 3D Analyst module of ESRI ArcGIS was used to create the depth points. TINS and contours were created step by step as several layers. Hence, the 3D Keelung harbor chart was developed, and the danger level for grounding the starboard was classified in order to underscore the degree of danger in each navigation area. Each segment in the figure represents risk indicators along the navigation route and their danger levels. Yellow means that the area ahead is becoming shallow and an alert should be issued. Red means the vessel is heading to an area with a grounding risk, and must consider turning. Flashing red means the collision and grounding avoidance procedures must be adhered to, and emergency measures taken.

In Fig. 10, starting from AP2 as defined by the expert rule base, the vessel is responding to the grounding risk using rudder angles. Right rudder angles of 10° and 15° would help the vessel to travel outside of the shallow water. Avoiding using any right rudder angle greater than 20° avoids the shallow water area more effectively. The constructed grounding alert model agrees with the actual design control requirements.

In this study, the system was also practiced using a ship-handling simulator. In addition to providing related fuzzy and operating parameters, prototype products were also completed by inserting a look up table in a memory chip. Practice tests were performed in Kinmen Harbor and Hualien Harbor.

CONCLUSIONS

In this study first the deepest draft point in the direction of navigation is used as the basic point. Along the navigation route, points are extracted and used to describe the cross sectional view of the seabed topography along the route. The WDSA used ranges from 0°-90° in 1° increments. After converting the depth points into continuous data, high resolution 3D data on any point along the route can be used to describe the cross sectional view of the seabed topography. The effect of warning distance, shallow water points, and underwater slope were then considered. First, the concept of WDSA was proposed. In experiment 1, the warning distance was improved from 65 m to 489 m. An expert rule base and a high alert rule base were constructed. Monitoring personnel onshore can choose the alert timing based on the properties of the monitored area. In the case where a high alert rule base is used in the VGA model, the timing can be shifted to an earlier time if the system membership functions have different blocks for these two rule bases. This study has completed tests under different sea conditions. A ship-handling simulator is used to perform a practice simulation. The lookup tables are manufactured into chips to complete practice tests in harbors.

When a vessel is sailing on the ocean, the location of a shallow water area ahead can only be roughly estimated from depth points and depth lines on the chart. It is impossible to find the location of the SWP for a grounding alert. Although monitoring can be performed onshore, for unknown stranding risks only the safety depth could be used to identify the safe areas for regional alert mode. The VGA model constructed in this study can effectively solve the problems it has so far faced. Search line segments can be used to screen vessels, in order to reduce the number of invalid alerts. By solving DAA, monitoring personnel can obtain the exact alert timing, and propose three indicators for a grounding alert (amber, red and flashing red/alarm). In this way, VTS operators and crewmembers can immediately obtain a clear warning to avoid danger zones in advance. The virtual alert system does not require facility maintenance, and AIS data are used. Under the 3D GIS platform, combined with a fuzzy algorithm, navigation results can be displayed on the Marine GIS. The aim was achieved of providing a system to aid in reducing groundings and assist in creating a green marine environment.

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