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# Fuzzy Risk Evaluator for Collision Avoidance Design of Vessels Based on Automatic Identification System

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Because of the high density of sea transportation, an effective solution for improving navigational safety is necessary. In this study, a warning system for the collision avoidance design of vessels is practically realized by integrating sensing messages delivered by an installed automatic identification system (AIS) and a fuzzy risk evaluator. Messages sent from the AIS include 1. the relative speed between any two selected vessels in the monitored open sea; 2. the distance between any two selected vessels; 3. the time of the closest point of approach, and 4. the distance of the closest point of approach. These four sensing messages extracted from the AIS are used as the inputs of the proposed fuzzy risk evaluator, and a fuzzy inference then makes an expert decision on the collision risk of any two selected vessels. The proposed system is programmed using the well-known software language C#, and a graphical user interface that can show the current positions of monitored vessels on Google Maps is also constructed. The proposed fuzzy risk evaluator can deliver real-time collision classification for all monitored ships, and the inference results can be used as reliable navigation guidelines for the collision avoidance design of vessels.

## 1. Introduction

Globalization has caused the rapid growth of sea transportation in recent years. In view of the growing sea traffic, the avoidance of collisions at sea is becoming more important. Sea accidents, which may involve damaged vessels, fire, sea pollution, and casualties, lead to economic and environmental damage.(1) The most frequent accidents are groundings, collisions, and fires.(2) Most of the accidents at sea are caused by vessel–vessel collisions in areas with high traffic density,(3,4) and the development of collision avoidance designs has become a major issue. The International Regulations for Preventing Collisions at Sea (COLREGS) formulated by the International Maritime Organization (IMO) give standard guidelines for moving seagoing

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vessels to follow to reduce the number of vessel–vessel collisions. A vessel traffic service (VTS) is a system used by sailors to avoid collisions between vessels. Most VTS systems use a radar, closed-circuit television (CCTV), a very high frequency (VHF) radiotelephone, and an automatic identification system (AIS) to monitor vessel trajectories and provide navigation safety in a limited area. Since 2002, every vessel with a weight over 300 tons has been required to fit a VTS, as stipulated by the International Convention for the Safety of Life at Sea (SOLAS). Although many facilities can scan the positions of vessels, collisions still occur because of human operation errors; hence, an intelligent pre-warning risk evaluator in a VTS for moving vessels is highly required to prevent collisions of ships. Since sea accidents caused by human operation errors may lead to considerable economic loss, we studied the extensive literature on vessel collision avoidance studies with the aim of reducing the number of vessel–vessel collisions. One study outlined a concept based on the use of the vessel domain to address the problem of vessel–vessel collisions.(5) A vessel domain is an area around a vessel that sailors or navigators should keep free from other vessels or solid objects.(6) A vessel domain is also associated with a near-collision situation between vessels,(7) and this concept has been improved by investigations.(8–12) Studies related to collision risk using different concepts have also been reported.(13–16) For example, Harrald *et al.* performed a simulation to model the impact of human operation error in a sea system.(17) Goerlandt and Montewka proposed a mathematical framework for the collision risk analysis of sea transportation systems.(18) Moreover, Zhang *et al.* developed a vessel conflict ranking operator to detect possible near-miss ship–ship collisions from AIS data.(19) Several collision risk studies that use AIS data have been reported. For instance, Mou *et al.* used AIS data to study collision avoidance in busy waterways.(20) Iperen classified vessel encounters from AIS data to monitor traffic safety in the North Sea.(21) Wen *et al.* developed a marine traffic complexity model to evaluate the status of traffic.(22) A collision risk evaluation system was achieved by using the ship model designed by Pratiwi *et al.*(23) Their achievement(23) requires background knowledge of all the considered vessels, such as their length, width, and type. The simulation results of their fuzzy inference system are promising, but this collision risk evaluation system cannot be used for the real-time monitoring of vessels for navigation, because it requires the accurate dimensions of all monitored vessels, which should be measured prior to its use. To overcome these problems, we developed a real-time collision risk evaluation system for navigation that gives an early warning of collision for surface vessels. This system integrates the measured data delivered from the sensing system. In the system, AIS data and an intelligent collision risk evaluator are used to effectively classify the instantaneous risk levels of vessel–vessel collisions without knowing the physical dimensions and models of surface vessels in advance. The main advantage of this system is that it can work in real time only using the following sensing messages measured by the AIS: distance, speed, the time of the closest point of approach (TCPA), and the distance of the closest point of approach (DCPA). To achieve real-time operation, the configuration of our proposed collision risk system consists of both hardware and software. In software designs, all subfunctions, such as the acquisition of the AIS data, the construction of the database, the proposed fuzzy risk evaluator, and the display function of vessels on Google Maps, are programmed in C#. To reduce the cost of the system, only an AIS module is utilized to monitor vessels on the open sea. The remainder of this paper is organized as follows. The procedures used to collect and measure the AIS data are introduced in Sect. 2, the proposed fuzzy risk evaluator is described in detail in Sect. 3, the real-time application of the collision risk evaluation system is analyzed in Sect. 4, and conclusions are given in Sect. 5.

## 2. Procedures of AIS Data Collection and Measurement

The collection of AIS messages is introduced in this section. First, the concept of the AIS is presented. Next, the process of collecting AIS messages is described. Figure 1 illustrates how the AIS data is collected in practice. Firstly, AIS and GPS messages are received by antennas. Secondly, the collected AIS messages are sent to a desktop PC with a C# application by the AIS transponder. Third, a function of the C# application converts the AIS messages to vessel data and sends the vessel data to a database server through the internet. Finally, the related trajectory data of vessels decoded from the AIS messages is displayed in real time on Google Maps and stored in the database server.

According to the rules of IMO and SOLAS, vessels of more than 300 tons operating in international seas should have an AIS installed. The AIS is integrated into a VTS to monitor and manage the trajectories of vessels in ports. In this system, a radar, vessels, a database, the internet, an electronic navigation chart (ENC), and a long-term record system are integrated. The AIS on a vessel can transmit AIS messages to other vessels through VHF communication. The AIS installed on a vessel can automatically transmit the messages about the vessel through the VHF at a specific time interval to a base station, to other vessels, and to flying equipment with an installed AIS receiver. By decoding the received AIS data, the maritime mobile service identity (MMSI), the speed over ground (SOG), and the course over ground (COG), the positions and types of vessels can be obtained. The AIS provides reliable and dynamical data on moving vessels, allowing sailors on other vessels to maintain navigation safety.

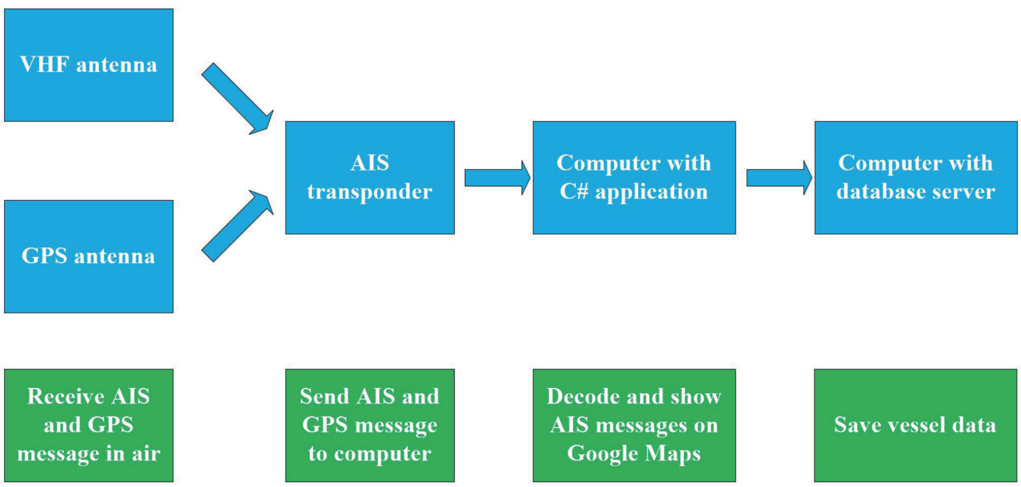



Fig. 1. (Color online) Flow chart of AIS data collection.

## 3. Fuzzy Risk Evaluator

The main objective of the proposed fuzzy risk evaluator is to determine a fuzzy risk that can be used for collision avoidance. It combines two main evaluators: a linguistic variable evaluator and a fuzzy risk evaluator. The measured data of monitored vessels obtained by the AIS station are stored in a data server and then transformed as inputs of linguistic variables for the linguistic variable evaluator. Figure 2 presents the structure of the fuzzy risk evaluator. A fuzzy rule table, an inference algorithm, and normalization are integrated to make a decision on the risk of collision between two monitoring vessels, and this evaluator is named the fuzzy risk evaluator. In the following, the linguistic variable and fuzzy risk evaluators are described in detail.

### 3.1 Linguistic variable evaluator

In this investigation, the distance, relative speed, TCPA, and DCPA are selected as candidate linguistic variables, whose values are derived from the measured data of the AIS stored in the data server, which include the SOG, COG, latitude, and longitude. The latitude, longitude, COG, and SOG for two vessels, A and B, are expressed as

$$\mathrm{A} : ( L_1, G_1, C_1, S_1 ), \tag{1}$$

$$\mathrm{B} : ( L_2, G_2, C_2, S_2 ), \tag{2}$$

where $L_1$, $G_1$, $C_{1,}$ and $S_1$ are the latitude, longitude, COG, and SOG of vessel A, respectively. Similarly, $L_2$, $G_2$, $C_2$, and $S_1$ are the latitude, longitude, COG, and SOG of vessel B, respectively.

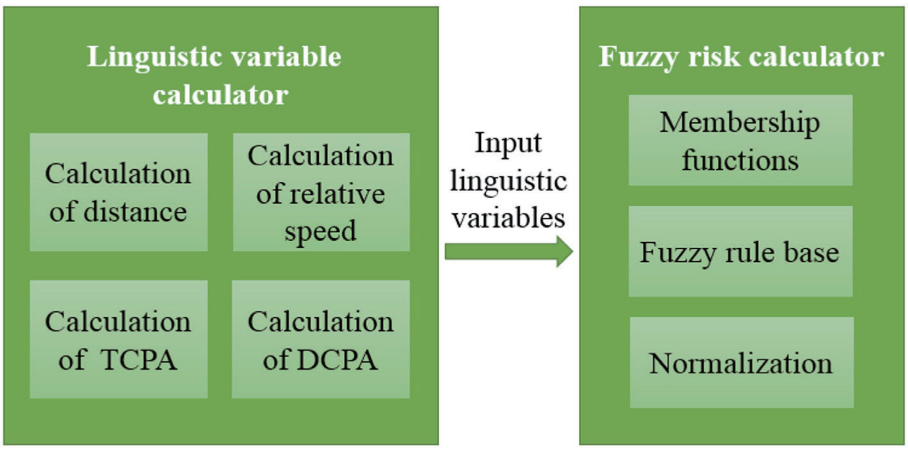



Fig. 2. (Color online) Structure of the fuzzy risk evaluator.

### 3.1.1 Calculation of distance between two vessels

The distance between two vessels is calculated using the "middle-latitude sailing" formula. Longitude, latitude, and COG data are utilized in this formula. The formulation is as follows:

$$l = L_1 - L_2, \tag{3}$$

$$DL_0 = G_1 - G_2, \tag{4}$$

$$L_m = \frac{L_1 + L_2}{2}, \tag{5}$$

$$P = DL_0 \times \cos(L_m), \tag{6}$$

$$Dist = \sqrt{P^2 + l^2}, \tag{7}$$

where $l$ is the difference in latitude, $DL_0$ is the difference in longitude, $L_m$ is the mean latitude, $P$ is the departure distance, and $Dist$ is the distance between two vessels.

### 3.1.2 Relative speed

In this study, the relative speed is positive when two vessels are moving toward each other and negative when they are moving away from each other. The SOG and COG contained in the received AIS messages can be used to calculate the relative speed $RS$ between two vessels as follows:

$$RS^2 = S_1^2 + S_2^2 - 2S_1S_2\cos(|C_1 - C_2|). \tag{8}$$

Figure 3 shows $RS$ with for two measured values of SOG, $SOG_1$ and $SOG_2$.

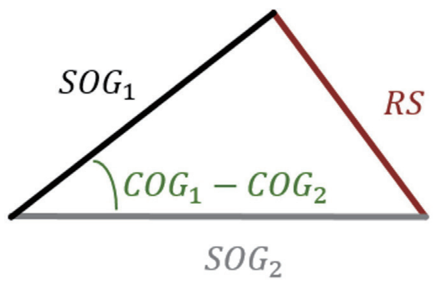



Fig. 3. (Color online) Relative speed calculated using the cosine law.

### 3.1.3 Calculation of TCPA

The time at which two vessels are closest is named the TCPA. It can be calculated as follows using the latitude and longitude coordinate method:

$$t_c = -\frac{l(S_1 \times \cos C_1 - S_2 \times \cos C_2) + P(S_1 \times \sin C_1 - S_2 \times \sin C_2)}{(S_1 \times \sin C_1 - S_2 \times \sin C_2)^2 + (S_1 \times \cos C_1 - S_2 \times \cos C_2)^2}, \tag{9}$$

where $t_c$ is the TCPA. If the TCPA is negative, then the closest point between the two moving vessels has already been reached and the vessels are moving away from each other.

### 3.1.4 Calculation of DCPA

The distance between two moving vessels at their closest point is defined as the DCPA, which is calculated as follows using the latitude and longitude coordinate method:

$$\begin{aligned} d_c = [&l^2 + 2l(S_1 \times \cos C_1 - S_2 \times \cos C_2)t_c + (S_1 \times \cos C_1 - S_2 \times \cos C_2)^2 t^2 \\ &+ P^2 + 2P(S_1 \times \sin C_1 - S_2 \times \sin C_2)t_c + (S_1 \times \sin C_1 - S_2 \times \sin C_2)^2 {t_c}^2]^{\frac{1}{2}}, \end{aligned} \tag{10}$$

where $d_c$ is the DCPA.

## 3.2 Fuzzy risk evaluator

In this section, we describe the fuzzy risk evaluator, which is developed by integrating the membership functions of distance, relative speed, TCPA, and DCPA. We also describe the fuzzy rule base and the defuzzification method. A flow chart of the proposed fuzzy risk evaluator is illustrated in Fig. 4.

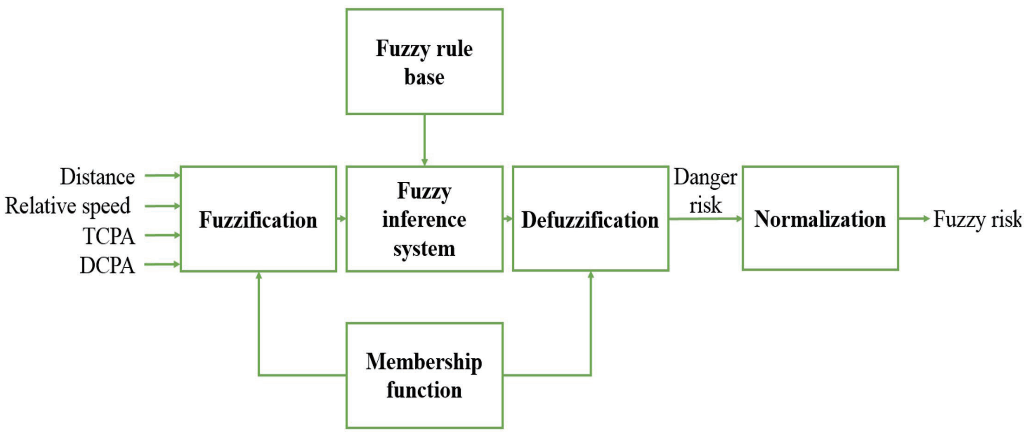



Fig. 4. (Color online) Flow chart of the proposed fuzzy risk evaluator.

### 3.2.1 Membership functions

The distance, relative speed, TCPA, DCPA, and danger risk are selected as linguistic variables of the proposed fuzzy risk evaluator. The membership functions of the selected linguistic variables are described as follows.

#### 3.2.1.1 Distance

Three triangular membership functions are set up [Eqs. (11)–(13)] and named Dclose, Dmiddle, and Dfar. According to the collision rules, the minimum distance between two vessels should be maintained as 0.9 nautical miles (NM). A longer distance between two vessels implies a safer situation. The average distance that vessels must keep to avoid colliding for each other on the open sea is 4 NM due to the radius of rotation of the vessels. We therefore define a safe distance between two moving vessels of 7 NM. On this basis, three membership functions, Dclose = [0.9, 0.9, 4], Dmiddle = [0.9, 4, 7], and Dfar = [4, 7, 7], are defined for the proposed method.

$$\mu_{\text{Dclose}}(x) = \begin{cases} 1 & \text{for } x \le 0.9 \\ \dfrac{4-x}{3.1} & \text{for } 0.9 \le x \le 4 \end{cases} \tag{11}$$

$$\mu_{\text{Dmiddle}}(x) = \begin{cases} \dfrac{x-0.9}{3.1} & \text{for } 0.9 \le x \le 4 \\ \dfrac{7-x}{3} & \text{for } 4 \le x \le 7 \end{cases} \tag{12}$$

$$\mu_{\text{Dfar}}(x) = \begin{cases} \dfrac{x-4}{3} & \text{for } 4 \le x \le 7 \\ 1 & \text{for } 7 \le x \end{cases} \tag{13}$$

Here, $\mu_{\text{Dclose}}$ is the Dclose membership function of the distance, $\mu_{\text{Dmiddle}}$ is the Dmiddle membership function of the distance, and $\mu_{\text{Dfar}}$ is the Dfar membership function of the distance.

#### 3.2.1.2 Relative speed

Three triangular membership functions for the relative speed, Eqs. (14)–(16), are set up and named RSslow, RSmiddle, and RSfast. Practically, the reporting interval of an AIS depends on the speed of the vessel. Table 1 shows reporting intervals for Class A shipborne mobile equipment. By referring to Table 1 and doubling the maximum speed, three membership functions are chosen to represent the relative speed: RSslow = [6, 6, 26], RSmiddle = [6, 28, 46], and RSfast = [28, 46, 46].

Table 1
Reporting intervals for Class A shipborne mobile equipment.

| Ship's dynamic conditions | Nominal reporting interval |
|---|---|
| Ship at anchor or moored and not moving faster than 3 knots | 3 min |
| Ship at anchor or moored and moving faster than 3 knots | 10 s |
| Ship moving at 0–14 knots | 10 s |
| Ship moving at 0–14 knots and changing course | 3 1/3 s |
| Ship moving at 14–23 knots | 6 s |
| Ship moving at 14–23 knots and changing course | 2 s |
| Ship moving at >23 knots | 2 s |
| Ship moving at >23 knots and changing course | 2 s |

$$\mu_{\mathrm{RSslow}}(x)=\begin{cases}1 & \text{for } x\le 6\\ \dfrac{28-x}{22} & \text{for } 6\le x\le 28\end{cases}\tag{14}$$

$$\mu_{\mathrm{RSmiddle}}(x)=\begin{cases}\dfrac{x-6}{22} & \text{for } 6\le x\le 28\\ \dfrac{46-x}{18} & \text{for } 28\le x\le 46\end{cases}\tag{15}$$

$$\mu_{\mathrm{RSfast}}(x)=\begin{cases}\dfrac{x-28}{18} & \text{for } 28\le x\le 46\\ 1 & \text{for } 46\le x\end{cases}\tag{16}$$

Here, $\mu_{\mathrm{RSslow}}$ is the RSslow membership function of the relative speed, $\mu_{\mathrm{RSmiddle}}$ is the RSmiddle membership function of the relative speed, and $\mu_{\mathrm{RSfast}}$ is the RSfast membership function of the relative speed.

### 3.2.1.3 TCPA

Three triangular membership functions for the TCPA, Eqs. (17)–(19), are defined with values of TCPAshort = [6, 6, 24], TCPAmiddle = [6, 24, 36], and TCPAlong = [24, 36, 36]. Negative values of the TCPA are disregarded because a negative value implies that the two vessels are moving away from each other and therefore a collision will not occur.

$$\mu_{\mathrm{TCPAshort}}(x)=\begin{cases}1 & \text{for } x\le 6\\ \dfrac{24-x}{18} & \text{for } 6\le x\le 24\end{cases}\tag{17}$$

$$\mu_{\text{TCPAmiddle}}(x) = \begin{cases} \dfrac{x-6}{18} & \text{for } 6 \le x \le 24 \\ \dfrac{36-x}{12} & \text{for } 24 \le x \le 36 \end{cases} \tag{18}$$

$$\mu_{\text{TCPAlong}}(x) = \begin{cases} \dfrac{x-24}{18} & \text{for } 24 \le x \le 66 \\ 1 & \text{for } 36 \le x \end{cases} \tag{19}$$

Here, $\mu_{\text{TCPAshort}}$ is the TCPAshort membership function of the TCPA, $\mu_{\text{TCPAmiddle}}$ is the TCPAmiddle membership function of the TCPA, and $\mu_{\text{TCPAlong}}$ is the TCPAlong membership function of the TCPA.

#### 3.2.1.4 DCPA

Three triangular membership functions for the DCPA, Eqs. (20)–(22), are defined with values of DCPAclose = [0, 0, 0.4], DCPAmiddle = [0, 0.4, 0.8], and DCPAfar = [0.4, 0.8, 0.8].

$$\mu_{\text{DCPAclose}}(x) = \begin{cases} 1 & \text{for } x \le 0 \\ \dfrac{0.4-x}{0.4} & \text{for } 0 \le x \le 0.4 \end{cases} \tag{20}$$

$$\mu_{\text{DCPAmiddle}}(x) = \begin{cases} \dfrac{x}{0.4} & \text{for } 0 \le x \le 0.4 \\ \dfrac{0.8-x}{0.4} & \text{for } 0.4 \le x \le 0.8 \end{cases} \tag{21}$$

$$\mu_{\text{DCPAfar}}(x) = \begin{cases} \dfrac{x-0.4}{0.4} & \text{for } 0.4 \le x \le 0.8 \\ 1 & \text{for } 0.8 \le x \end{cases} \tag{22}$$

Here, $\mu_{\text{DCPAclose}}$ is the DCPAclose membership function of the DCPA, $\mu_{\text{DCPAmiddle}}$ is the DCPAmiddle membership function of the DCPA, and $\mu_{\text{DCPAfar}}$ is the DCPAfar membership function of the DCPA.

#### 3.2.1.5 Danger risk

The danger risk is the output linguistic variable of the proposed fuzzy risk evaluator. Three triangular membership functions for the danger risk, Eqs. (23)–(25), are set up with values of safe = [0, 0, 50], middle = [0, 50, 100], and dangerous = [50, 100, 100]. These outputs are defined according to the results of experiments carried out by experts in ocean borne vessels.

$$\mu_{\mathrm{DRsafe}}(y) = \begin{cases} 1 & \text{for } y \le 0 \\ \dfrac{50-y}{50} & \text{for } 0 \le y \le 50 \end{cases} \tag{23}$$

$$\mu_{\mathrm{DRmiddle}}(y) = \begin{cases} \dfrac{y}{50} & \text{for } 0 \le y \le 50 \\ \dfrac{100-y}{50} & \text{for } 50 \le y \le 100 \end{cases} \tag{24}$$

$$\mu_{\mathrm{DRdangerous}}(y) = \begin{cases} \dfrac{y-50}{50} & \text{for } 50 \le y \le 100 \\ 1 & \text{for } 100 \le y \end{cases} \tag{25}$$

Here, $\mu_{\mathrm{DRsafe}}$ is the DRsafe membership function of the danger risk, $\mu_{\mathrm{DRmiddle}}$ is the DRmiddle membership function of the danger risk, and $\mu_{\mathrm{DRdangerous}}$ is the DRdangerous membership function of the danger risk.

### 3.2.2 Fuzzy rule table

In this investigation, four linguistic variables, distance, relative speed, TCPA, and DCPA, are selected for use in the collision risk evaluator of vessels. A total of 81 rules, some of which are listed in Table 2, are applied.

Table 2
Fuzzy rule table of the collision risk evaluator.

| No. | Distance | Relative Speed | TCPA | DCPA | Danger Risk |
|---|---|---|---|---|---|
| 1 | Far | Slow | Long | Far | Safe |
| 2 | Far | Slow | Long | Middle | Safe |
| 3 | Far | Slow | Long | Close | Safe |
| 4 | Far | Slow | Middle | Far | Safe |
| 5 | Far | Slow | Middle | Middle | Safe |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 77 | Close | Fast | Middle | Middle | Dangerous |
| 78 | Close | Fast | Middle | Close | Dangerous |
| 79 | Close | Fast | Short | Far | Dangerous |
| 80 | Close | Fast | Short | Middle | Dangerous |
| 81 | Close | Fast | Short | Close | Dangerous |

### 3.2.3 Defuzzification

The mostly common method of defuzzification is the center of gravity defuzzification (CGD). CGD is applied to calculate the danger risk in this research as follows:

$$y_{CGD} = \frac{\sum_{i=1}^{k} y_i \mu_D(y_i)}{\sum_{i=1}^{k} \mu_D(y_i)}, \tag{26}$$

where $y_{CGD}$ is the danger risk, $k$ is the number of outputs, $y_i$ is the output value, and $M_D(y_i)$ represents the membership value in fuzzy set $D$.

### 3.2.4 Normalization

Because the inferred fuzzy danger risk is not distributed within the range [0, 100], it is normalized as follows:

$$y_{FR} = \left| \frac{y_{CGD} - \text{Max}\{y_{CGD}\}}{\text{Max}\{y_{CGD}\} - \text{Min}\{y_{CGD}\}} \right| \times 100, \tag{27}$$

where $y_{FR}$ is the fuzzy risk output. As a result, a modified danger risk in the range [0, 100] is obtained.

## 4. System Implementation and Experiment

The implementation of the system and an experiment are introduced in this section. The proposed risk evaluator consists of software and hardware, as described in Sect. 4.1. The experimental results are discussed by considering several real events in Sect. 4.2.

### 4.1 Configuration of experiment environment

In this section, the structure of the proposed system is explained and the setting for real cases is discussed. The hardware of the proposed system includes a VHF antenna, an AIS transponder, and a database server. The software of the proposed system includes a C# application to decode messages of the AIS and evaluate the fuzzy risk. The data server is used to store the records of all vessels within the detectable radius of the AIS station.

### 4.1.1 System structure

The structure of the overall system is shown in Fig. 5. Firstly, the VHF and GPS antennas receive the AIS and GPS messages, respectively, and transmit them to the AIS transponder.

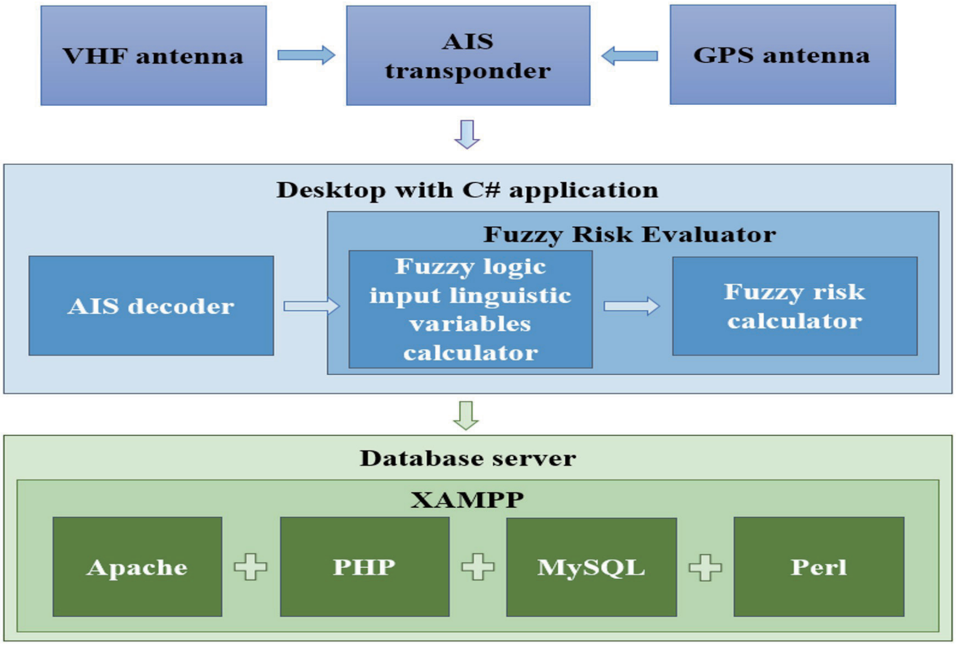



Fig. 5. (Color online) Overall structure of the proposed system.

Secondly, the AIS transponder sends the AIS and GPS messages to a desktop PC with the developed C# application. Thirdly, the C# application decodes the AIS messages as sensing messages for the subsequent fuzzy risk evaluation and stores the sensing messages in the database server. As shown in Fig. 5, the desktop PC is used to decode the AIS envelope as the sensing messages and evaluate in real time the danger risk for any two monitored vessels. The database server is installed in an XAMPP software platform that contains Apache, PHP, MySQL, and Perl.

#### 4.1.2 System setting

In this study, the VHF and GPS antennas of the AIS base station are installed on the roof of the Department of Systems and Naval Mechatronic Engineering (SNME) of National Cheng Kung University, as shown in Fig. 6.

The red frame in Fig. 7 indicates the functions of the C# application, which decodes the AIS messages to vessel data, displays the data on Google Maps, and sends the vessel data to the database server.

### 4.2 Real experiments

In this section, the results of three real experiments using the proposed method are presented and compared with those of a fuzzy collision risk method[23] that utilizes the TCPA and DCPA as inputs. All the AIS data for this comparison method are measured from the three experiments. The first experiment involves a dangerous situation of two vessels with a very high risk of


Fig. 6. (Color online) GPS and VHF antennas.

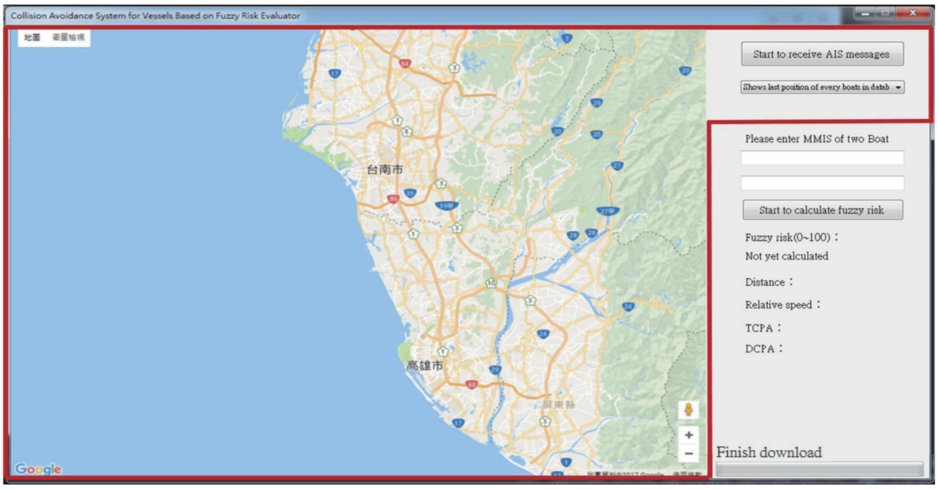
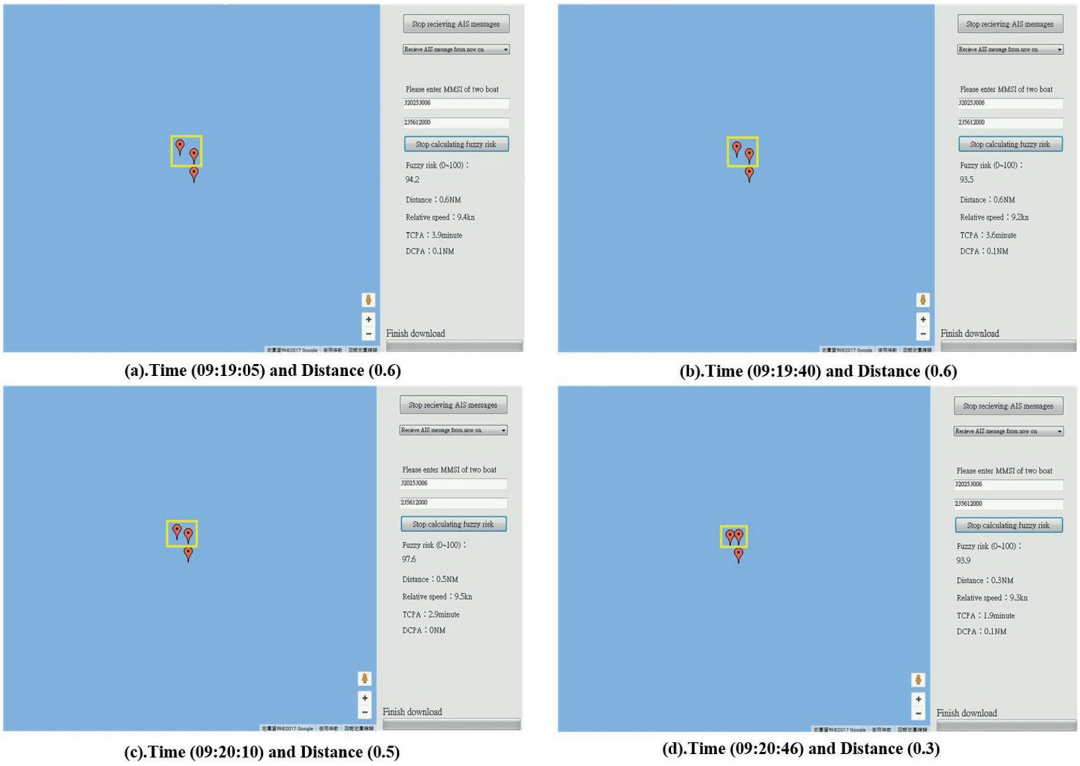



Fig. 7. (Color online) User interface of C# application.

collision. The second experiment involves a medium level of danger of collision. The third experiment involves two vessels with no danger of collision.

### 4.2.1 Dangerous situation

The real-time risk evaluation of collision between vessel A (MMSI #320253006) and vessel B (MMSI #235612000) by using this method is illustrated in Fig. 8. This is an emergency case in which the people on board both ships should be evacuated. As mentioned above, the distance, relative speed, TCPA, and DCPA mainly determine the output of the proposed fuzzy risk evaluator. In this case, vessels A and B are enclosed in yellow boxes in Google Maps, and the real-time collision risk is evaluated at regular time intervals as shown in Fig. 8. The inference results of the proposed and comparison methods are presented in Tables 3 and 4, respectively. From Table 3, it is clear that the relative distance between vessels A and B decreases gradually, the TCPA decreases gradually, the DCPA remains within 0–0.1, and the relative speed remains



**(a).Time (09:19:05) and Distance (0.6)**
**(b).Time (09:19:40) and Distance (0.6)**
**(c).Time (09:20:10) and Distance (0.5)**
**(d).Time (09:20:46) and Distance (0.3)**

Fig. 8. (Color online) Situation with high risk of collision between vessel A (MMSI #320253006) and vessel B (MMSI #235612000).

Table 3
Inference results of fuzzy risk evaluation of collision between vessel A (MMSI #320253006) and vessel B (MMSI #235612000) for proposed method.

| Time (hr:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 09:19:05 | 0.6 | 9.4 | 3.9 | 0.1 | 94.2 |
| 09:19:40 | 0.6 | 9.2 | 3.6 | 0.1 | 93.5 |
| 09:20:10 | 0.5 | 9.5 | 2.9 | 0 | 97.6 |
| 09:20:46 | 0.3 | 9.3 | 1.9 | 0.1 | 93.9 |

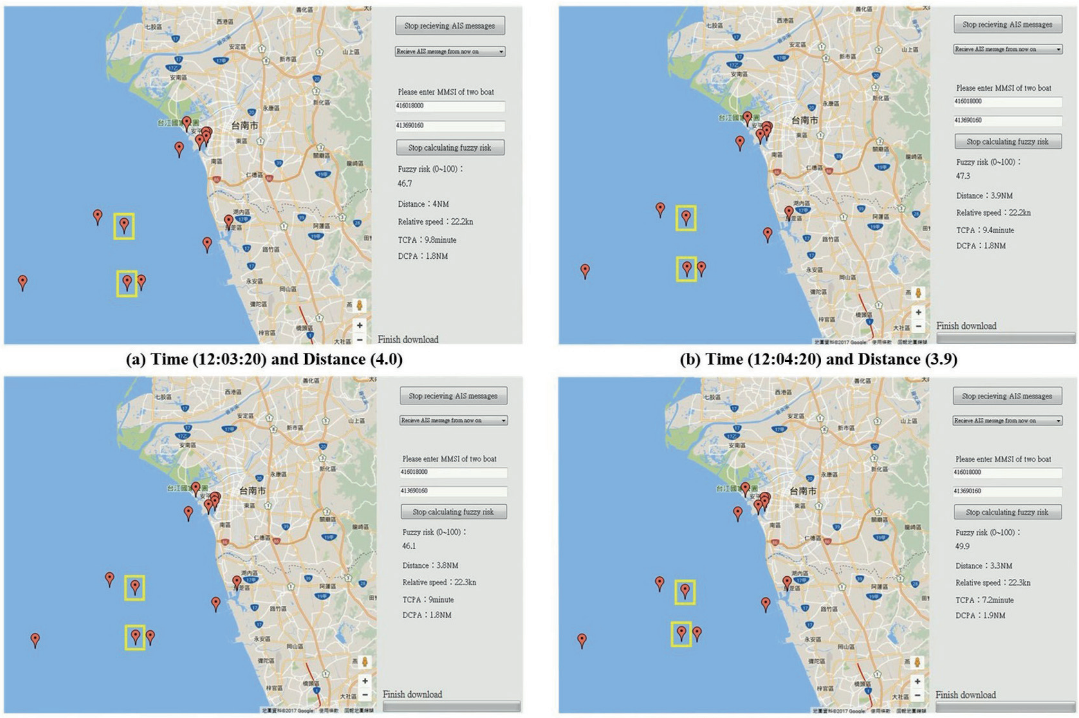
Table 4
Inference results of fuzzy risk evaluation of collision between vessel A (MMSI #320253006) and vessel B (MMSI #235612000) for comparison method.

| Time (hr:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 09:19:05 | 0.6 | 9.4 | 4.8 | 0.2 | 90.1 |
| 09:19:40 | 0.6 | 9.2 | 4.5 | 0.3 | 89.4 |
| 09:20:10 | 0.5 | 9.5 | 3.8 | 0.1 | 92.5 |
| 09:20:46 | 0.3 | 9.3 | 2.8 | 0.3 | 88.9 |

within 9.2–9.5 kn. On the basis of these values, our proposed fuzzy evaluator infers that the real-time risk values are 94.2, 93.5, 97.6, and 93.9. These are reasonable results because in this case, the two monitored vessels are close to each other throughout the experiment. According to the results, the performance of the proposed method is superior to that of the comparison method.

#### 4.2.2 Medium-risk situation

For this experiment, the fuzzy risk evaluation of collision between vessel A (MMSI #416048000) and vessel B (MMSI #413690160) is displayed in Fig. 9. The calculated distance, relative speed, and TCPA have intermediate values, and the DCPA values are 1.9 and 1.0 NM for the proposed and comparison methods, respectively. Thus, the real-time evaluated risks for the proposed and comparison methods also have intermediate values. The real-time distance, relative speed, TCPA, DCPA, and risk for the two methods are listed in Tables 5 and 6, which show that the proposed method has superior performance to the comparison method.




(a) Time (12:03:20) and Distance (4.0) (b) Time (12:04:20) and Distance (3.9)

(c) Time (12:05:33) and Distance (3.8) (d) Time (12:06:57) and Distance (3.3)

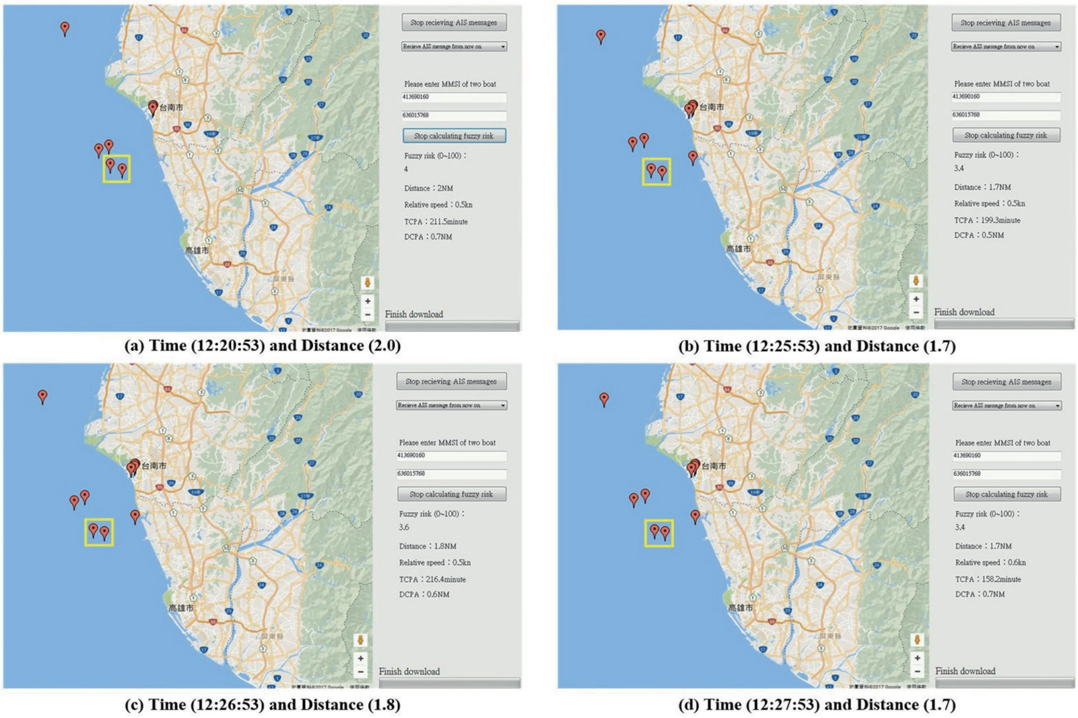
Fig. 9. (Color online) Situation with medium risk of collision between vessel A (MMSI #416048000) and vessel B (MMSI #413690160).

Table 5
Results of fuzzy risk evaluation of collision between vessel A (MMSI #416048000) and vessel B (MMSI #413690160) for proposed method.

| Time (h:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 12:03:20 | 4 | 22.2 | 9.8 | 1.8 | 46.7 |
| 12:04:20 | 3.9 | 22.2 | 9.4 | 1.8 | 47.3 |
| 12:05:33 | 3.8 | 22.3 | 9 | 1.8 | 46.1 |
| 12:06:57 | 3.3 | 22.3 | 7.2 | 1.9 | 49.9 |

Table 6
Results of fuzzy risk evaluation of collision between vessel A (MMSI #416048000) and vessel B (MMSI #413690160) for comparison method.

| Time (h:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 12:03:20 | 4 | 22.2 | 10.7 | 2.6 | 43.5 |
| 12:04:20 | 3.9 | 22.2 | 10.3 | 2.5 | 44.1 |
| 12:05:33 | 3.8 | 22.3 | 9.9 | 2.5 | 42.9 |
| 12:06:57 | 3.3 | 22.3 | 8.1 | 2.6 | 46.3 |



(a) Time (12:20:53) and Distance (2.0)
(b) Time (12:25:53) and Distance (1.7)
(c) Time (12:26:53) and Distance (1.8)
(d) Time (12:27:53) and Distance (1.7)

Fig. 10. (Color online) Safe situation with low risk of collision between vessel A (MMSI #413690160) and vessel B (MMSI #636015768).

### 4.2.3 Safe situation

For this experiment, the fuzzy risk evaluation of collision between vessel A (MMSI #413690160) and vessel B (MMSI #636015768) is exhibited in Fig. 10. Intuitively, the distance, relative speed, TCPA, and DCPA indicate a safe situation, and the inferred fuzzy risk ranges from 3.1 to 4 for the proposed and comparison methods. Tables 7 and 8 show the real-time measured values of distance, relative speed, TCPA, DCPA, and fuzzy risk for the two methods. The proposed method also demonstrates superior results to the comparison method in the safe situation.

The tests of the proposed and comparison methods for the three real scenarios show that the proposed method is superior to the compared method regardless of the predicted risk under the same testing conditions. Moreover, our proposed method has the advantage of not requiring background knowledge of the ship domain that must be collected in advance.

Table 7
Results of fuzzy risk evaluation of collision between vessel A (MMSI #413690160) and vessel B (MMSI #636015768) for proposed method.

| Time (h:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 12:20:53 | 2 | 0.5 | 211.5 | 0.7 | 4 |
| 12:25:53 | 1.7 | 0.5 | 199.3 | 0.5 | 3.4 |
| 12:26:53 | 1.8 | 0.5 | 216.4 | 0.6 | 3.6 |
| 12:27:53 | 1.7 | 0.6 | 158.2 | 0.7 | 3.4 |

Table 8
Results of fuzzy risk evaluation of collision between vessel A (MMSI #413690160) and vessel B (MMSI #636015768) for comparison method.

| Time (h:min:s) | Distance (NM) | Relative speed (kn) | TCPA (min) | DCPA (NM) | Fuzzy risk |
|---|---|---|---|---|---|
| 12:20:53 | 2 | 0.5 | 219.4 | 1.3 | 3.8 |
| 12:25:53 | 1.7 | 0.5 | 207.2 | 0.9 | 3.1 |
| 12:26:53 | 1.8 | 0.5 | 224.3 | 1.1 | 3.4 |
| 12:27:53 | 1.7 | 0.6 | 164.1 | 1.2 | 3.2 |

## 5. Conclusions

We proposed a fuzzy risk evaluator for providing an effective real-time collision avoidance alarm for oceangoing vessels navigating areas with a high density of ships. This real-time fuzzy collision avoidance alarm has four calculable inputs, relative distance, relative velocity, TCPA, and DCPA, which can be calculated from the data decoded by the AIS to infer the risk of collision of any two monitored vessels. Unlike the conventional design, the developed visible user interface, which can indicate the risk of collision, provides an easy-to-understood display and a pre-alarm for sailors controlling vessels. According to the results of experiments involving real situations, the proposed fuzzy risk evaluator delivers highly precise evaluations of the collision risk when monitoring any vessel, enabling sailors to act accordingly and avoid possible collisions. Moreover, the system uses an AIS without any extra sensors. Thus, an effective and low-cost collision avoidance alarm that has been thoroughly tested for evaluating the risk of vessel collision on the open sea has been practically achieved.

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