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A Fuzzy Logic Method for Collision Avoidance in Vessel Traffic Service

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Currently Vessel Traffic Service (VTS) does not have enough technical capability to monitor a crowded surveillance area to maintain safety. Without an efficient alerting system, many marine accidents have occurred due to operator oversight. In this article, a new fuzzy logic method is proposed to add vessel collision avoidance capability to VTS/AIS systems for all potential collision ships in the surveillance area. Starting from the VTS standpoint and integrating AIS data into the Marine Geographic Information System (MGIS) as a platform, the calculations of ship domain and ship inertial force are utilized to generate models of a guarding ring and danger index. By this means, a precise prediction of collision time and position can be achieved using a marine GIS spatial analyst module. The proposed method is able to enhance the VTS operator's decision-making abilities by providing a collision avoidance alerting system.

KEY WORDS

1. Collision avoidance. 2. VTS. 3. MGIS. 4. AIS.

1. INTRODUCTION.

How to prevent collisions at sea or in harbour is an important problem for the on-duty navigator or VTS operator (Sato et al., 1998). When an officer of the watch (OOW) is made aware of a collision risk by navigational equipment such as ARPA, ECDIS or AIS, he should take action to avoid the risk of collision. In general, the OOW observes radar to obtain the bearing and range of target ships, which do not represent true motion, but the relative motion observed between two ships. The traditional radar plotting methods of Closest Point of Approach (CPA) and Time of Closest Point of Approach (TCPA), using plotting techniques and the Motion of Target (MOT) vector triangle, have been used to determine the possibility of collision by crossing between two vessels on space and time axes. If the OOW finds the safety margin less than the CPA/TCPA limit, then ship handling for collision avoidance should be done in compliance with the international regulations for preventing collisions at sea (COLREGS). Modern ARPA electronic navigation equipment with collision avoidance operates on the basis of these concepts. On the other hand, VTS radar monitors vessels entering and leaving port on the basis of the true motion of the vessels in the area under surveillance. It can be likened to a celestial observer serving all the vessels around the harbour within a range of 20 nautical miles. Moreover, VTS can calculate the danger factor between each pair of moving vessels by calculating true motion via

CPA and TCPA factors using high-speed computers (Smeaton et al., 1990). These two factors, CPA and TCPA, are key to determining navigation safety, as they indicate the observed course of ships, not the current heading of ships. Therefore, the on-duty VTS operator or OOW can be easily confused about the potential collision risk, especially under rough sea conditions. When monitoring multiple target ships, ARPA cannot provide the function of estimating risk of collision among these target ships.

To achieve navigational safety, VTS must be able to obtain full information about each participating vessel. A new technology, known as AIS, promises to enhance safety of navigation and allow traffic managers to do their jobs more safely and effectively (Giuliano, 2003). Compared with the functions of ARPA, AIS provides more complete dynamic and static data on the target ships in real time. The dynamic data include ship position, indication and integrity, position time stamp, course over ground, speed over ground, heading, navigational status and rate of turn (ROT). The static data include vessel name, call sign, length and beam, type of ship, IMO (International Maritime Organization) number, GPS (Global Positioning System) antenna location and height over keel. However some drawbacks of AIS could diminish its ability as a collision avoidance mechanism. These include incorrect settings for static data, poor antenna sitting and the effect of Class B AIS (Stitt, 2004). Furthermore, ARPA is not effective for collision avoidance with intermittent targets at relatively close range in sea clutter and radar blind area conditions, but AIS has enough information to solve these problems. Taking advantage of high-speed networks, VTS systems could be quickly upgraded based on AIS data.

Successful implementation of AIS-based VTS systems will substantially enhance safety and improve control and surveillance of vessel traffic at sea. The most advanced digital VTS/AIS systems can display and record raw AIS data in the form of a tactical traffic playback image. In such a system, vessels are displayed as icons on an Electronic Chart Display and Information System (ECDIS). However, ECDIS has no function to analyze AIS data to obtain the collision risk among target ships. MGIS is a new type of digital information system with the capability to combine a wide range of four-dimensional oceanographic and coastal data to create environmental scenarios. The integration of a MGIS as a platform for a VTS/AIS collision alert system is a new concept in nautical digital computer systems. Two programming languages have been used as an integrating framework via communication port for VTS/AIS and MGIS. The development of VTS/AIS systems with MGIS integrate various types of data that can be used for navigation safety. Thus, MGIS is more capable of dealing with navigational safety management than ECDIS, when performing the 3D simulation of collision avoidance in the harbour channel for ships of different under keel clearance.

The purpose of this paper is to present a method for improving navigational safety for on-shore VTS systems providing surveillance to vessels entering and leaving port (Fujii and Tanaka, 1971). For a large number of target ships at sea, it is difficult for ARPA to compute the collision risk based on true motion due to system restrictions and the scope of the computer analysis (Lamb, 1985 and Lamb et al., 1995). However, these problems can be alleviated using integrated AIS/MGIS systems with the proposed fuzzy logic method. In this study, the models of guarding ring and danger index are calculated based on AIS data and MGIS analysis and a mapping technique on the space and time axes. The range of the guarding ring and the value of the danger index are determined by fuzzy logic with several parameters including ship size, speed and sea state. The calculation of danger index is based on the variation of straight distance and slope of the radical axis of two circles. The potential collision point and danger level are estimated on time and space axes by real-time simulation (Davis and Stockel, 1980). In the proposed integrated VTS/AIS/GIS system, the VTS operator is able to make effective decisions in a collision alerting system environment (Fujii and Tanaka, 1971).

2. VTS/AIS/MGIS INTEGRATED SYSTEM.

VTS systems are designed, not only to improve navigational safety and efficiency of vessel traffic, but also to protect the marine environment within the surveillance area (Coldwell, 1983). A Marine GIS is a combination of hardware, software and nautical data that enables users to store and maintain large quantities of geographically referenced information, perform complex analyses on data, and easily make changes to marine information. Based on the integrated concept in nautical digital systems, the MGIS is considered as a platform in the VTS/AIS collision alert system. Following the current IMO standards for AIS, specifically AIS NMEA-0183 which specifies the system protocol, the C++ and AVENUE languages have been used as a programming framework for VTS/AIS and MGIS. Thus the VTS/AIS/MGIS integrated system has been developed as a way to provide collision avoidance alert system for VTS.

For the integration of VTS and AIS, AIS in compliance with IMO regulations provides information according to the NMEA-0183 protocol. Therefore, the proposed VTS system has been integrated using C++ external functions and the AVENUE language of MGIS to convert data from RS-422 to RS-232 I/O ports. The sorted time series information is stored in the MGIS database with a GPS time stamp. Using spatial mapping and time analysis algorithms, the data for the vessel collision alert system are calculated in accordance with AIS data, harbour weather reports and navigational safety information. The calculated result is displayed in the proposed VTS/AIS/MGIS integrated system using international standard chart symbols. For vessels without AIS, radar image data will be integrated via digital VTS. This study proposes high-speed calculation and real-time information update within MGIS, which achieves much better results than current ECDIS systems in a VTS/AIS application.

3. MODEL OF ALERT SYSTEM.

The proposed alert system for VTS/AIS/MGIS is based on the concept of a danger index (radical axis method) and fuzzy guarding ring. In the proposed method, the size of the guarding ring is determined by the fuzzy logic method and the danger index for vessel collision is calculated by the MGIS algorithm. The details of these concepts are described below.

3.1. *Radical axis of the guarding ring*. The radical axis is a line passing through the intersection points of two guarding rings. Ship navigation can be considered as particle motion in the VTS, and the length variation of the radical axis can be considered as a collision alert index that is used to determine the collision risk of

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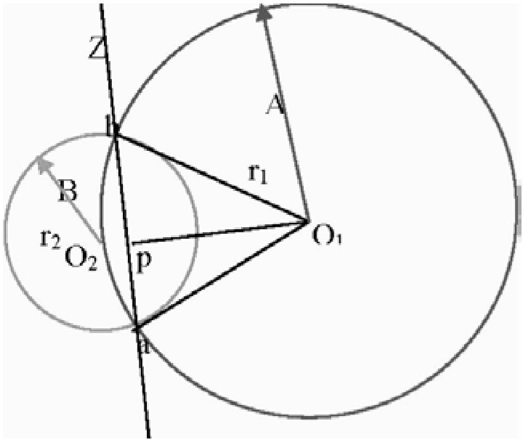

Figure 1. The radical axis of two guarding rings.

the vessel. Basically, the length of the radical axis increases whenever two ships are approaching. The mathematical description of this concept is listed as follows:

Figure 1 shows the line of the radical axis, *ab*, of two circles O_1 and O_2. As can be seen in this figure, O_1 represents the target ship 1 and O_2 represents the target ship 2 as situated by AIS antenna location. According to the Pythagorean theorem, the line *ab* increases whenever the distance between two circles O_1 and O_2 decreases. This mathematical concept is useful for the collision alert system that will be discussed later.

3.2. *Model of the fuzzy guarding ring*. The fuzzy guarding ring for the integrated system is derived from the concept of the ship domain, which is an area around the vessel that the navigator wants to keep clear of other ships (Goodwin 1975). In general, experienced navigators define the safety range by experience and estimate a clearance (e.g. two nautical miles) to maintain between their own ship and any other target ship. Therefore, the clearance is an imprecise value that is determined by ship manoeuvring, ship speed and weather conditions (Zhu et al., 2001 and Zhao et al., 1993). Based on AIS data, ship domain and fuzzy logic theory, the size of the guarding ring is determined.

Many marine science researchers have used fuzzy logic to develop control systems for collision avoidance. The basic configuration of a fuzzy logic system, as shown in Figure 2, consists of four principal elements: the fuzzifier, the fuzzy rule base, the inference engine, and the defuzzifier.

In the proposed method, the fuzzifier uses a singleton method to map a crisp point into a fuzzy set and the fuzzy rule base comprises a collection of fuzzy multiple-input single-output (MISO) IF-THEN rules. The fuzzy inference engine performs a mapping from fuzzy sets, based on the fuzzy if-then rules in the fuzzy rule base and the compositional rules of inference. In the defuzzifier, the centre of area (COA) is used for calculating a crisp output from the system (Kacprzyk, 1997). The fuzzy domain of the guarding ring (GR) is calculated using three input linguistic variables (Lee et al., 2004): L (length of ship), V (speed of ship) and S (sea state), and one output linguistic variable D (radius of guarding ring). According to Goodwin's statistical analysis of ship domain, the minimum distance between vessels is 0·9 nautical miles

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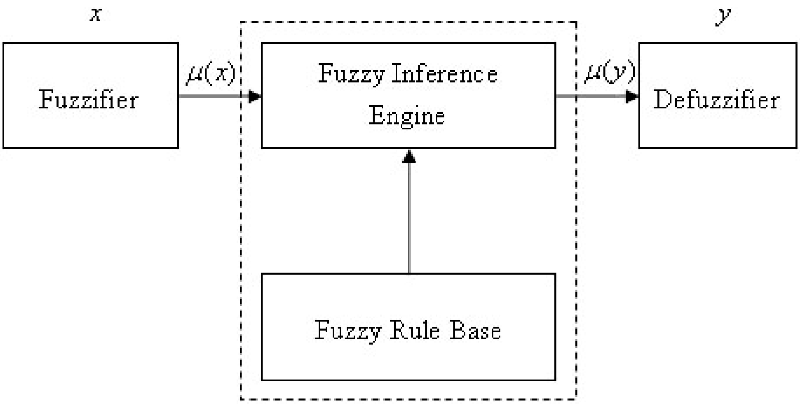

Figure 2. Typical architecture of a fuzzy system.

(Bonissone, 1982). Therefore, the formula for the modified radius of the guarding ring is calculated as: $MR = 0{\cdot}9 + D$ nautical miles.

The linguistic variable "ship size" (L) is calculated based on the data of 420 AIS-equipped ships that was gathered and analyzed by ClassNK (Nippon Kaiji Kyokai), a ship classification society in Japan (www.classnk.or.jp). According to the statistical analysis, ship size values of 130/190/250 metres are taken to correspond to linguistic variable values of small, medium and large.

The first step is to describe the linguistic variable of ship size on the universal discourse set $U_{\text{size}} = [130, 250]$ and operating domain of x (base variable) representing ship size in metres, using triangular and partial trapezoidal membership functions which specify the terms small, medium and large, these three linguistic terms can be converted to the following fuzzy numbers: "small" = (0,0,130,190), "medium" = (130,190,190,250), "large" = (190,250,250,250), using triangular and partial trapezoidal membership functions which specify the terms small, medium and large as shown in Figure 3(a). The ship size membership functions of these terms are:

$$\mu_{small}(x) = \begin{cases} 1 & \text{for } x \leqslant 130 \\ \dfrac{190 - x}{60} & \text{for } 130 \leqslant x \leqslant 190 \end{cases}; \quad \mu_{med}(x) = \begin{cases} \dfrac{x - 130}{60} & \text{for } 130 \leqslant x \leqslant 190 \\ \dfrac{250 - x}{60} & \text{for } 190 \leqslant x \leqslant 250 \end{cases};$$

$$\mu_{large}(x) = \begin{cases} \dfrac{x - 190}{60} & \text{for } 190 \leqslant x \leqslant 250 \\ 1 & \text{for } 250 \leqslant x \end{cases}$$

The linguistic variable "ship speed" (V) is defined with reference to the AIS transmission time interval for different class-A vessels, in compliance with ITU-R recommendation M1371-1. In the inner harbour, vessel speed should not exceed 5 knots (COG) according to the COLREGS. In addition, ship speed and transmission

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Table 1. The shipboard AIS (Class A) reporting time interval.

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 0–14 knots	10 s
Ship 0–14 knots and changing course	3 1/3 s
Ship 14–23 knots	6 s
Ship 14–23 knots and changing course	2 s
Ship >23 knots	2 s
Ship >23 knots and changing course	2 s

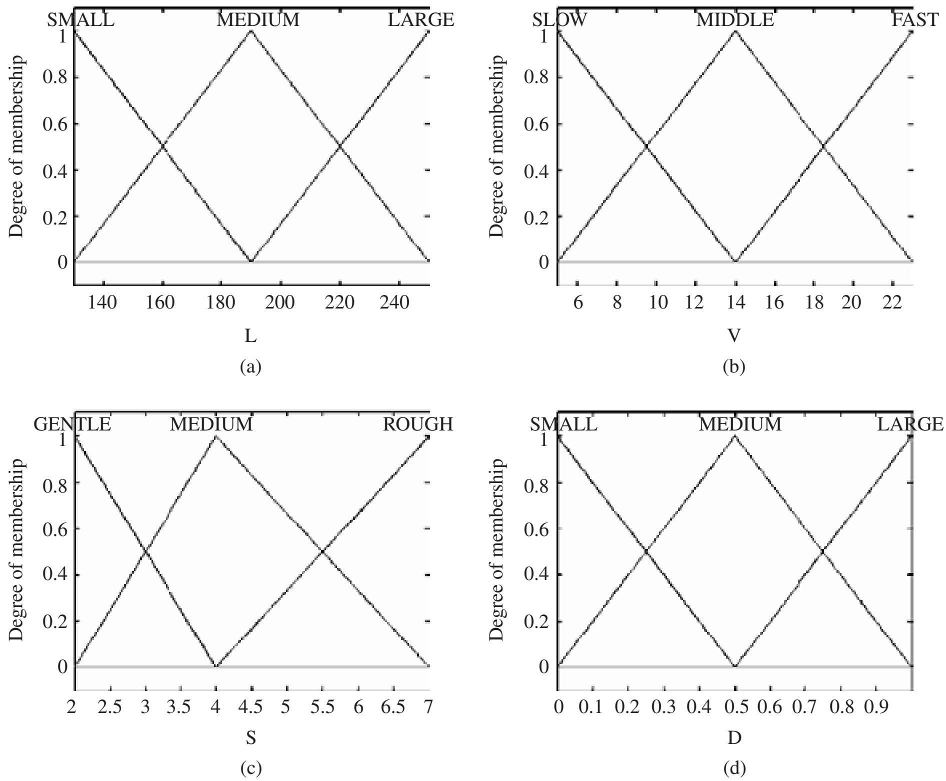

Figure 3. The membership functions of the terms (a) ship size (L(x): small, medium and large) (b) ship speed (V(y): slow, medium and fast) (c) sea state (S(z): gentle, medium and rough (d) radius size of guarding ring (GR(r): small, medium and large.

interval are directly proportional to each other, hence values of 5/14/23 knots can be taken to correspond to values of slow, medium and fast for the ship speed linguistic variable. The nominal reporting interval for AIS depends on the ship's dynamic conditions. For instance, the report time interval is 3 minutes when ship at anchor or moored and not moving faster than 3 knots, as shown in Table 1. The next step is to describe the ship speed linguistic variable on the universal

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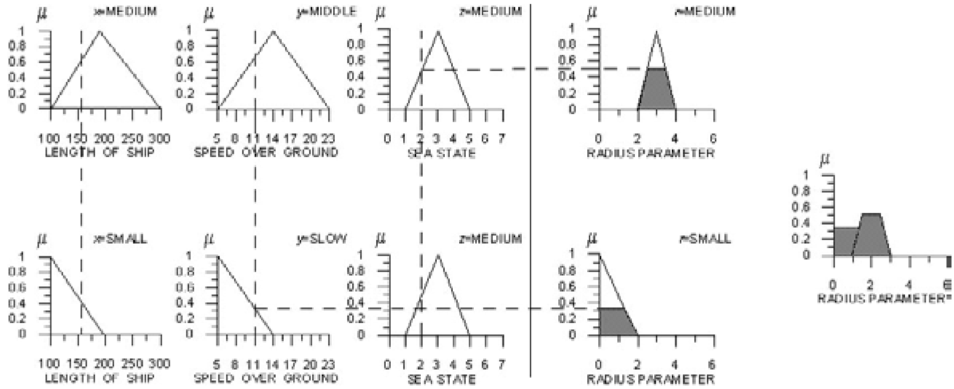

Figure 4. The fuzzy reasoning of max-min composition.

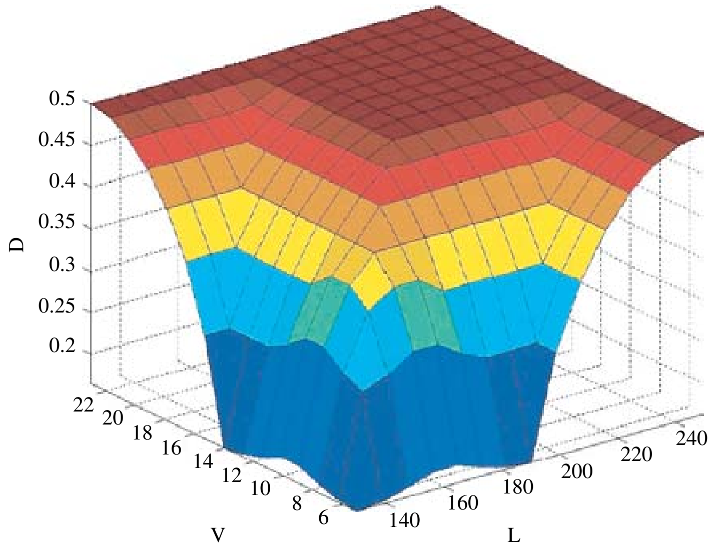

Figure 5. Surface graphic of output values D (on sea state 2).

discourse set $U_{speed}=[5, 23]$ and the operating domain of y representing ship speed in knots (see Figure 3(b)) by triangular and partial trapezoidal membership functions which specify the values of slow (5,5,5,14), medium (5,14,14,23) and fast (14,23,23,23).

The speed membership functions of these terms are:

$$\mu_{slow}(y)=\begin{cases} 1 & for\ y\leqslant 5 \\ \dfrac{14-y}{9} & for\ 5\leqslant y\leqslant 14 \end{cases};\quad \mu_{med}(y)=\begin{cases} \dfrac{y-5}{9} & for\ 5\leqslant y\leqslant 14 \\ \dfrac{23-y}{9} & for\ 14\leqslant y\leqslant 23 \end{cases};$$

$$\mu_{fast}(y)=\begin{cases} \dfrac{y-14}{9} & for\ 14\leqslant y\leqslant 23 \\ 1 & for\ 23\leqslant y \end{cases}$$

The third step is to describe the linguistic variable "sea state" on the universal discourse set $U_{\text{state}}=[2, 7]$ and the operating domain of z representing ship size in metres (see Figure 3(c)) by triangular and partial trapezoidal membership functions which specify the terms gentle (2,2,2,4), medium (2,4,4,7) and rough (4,7,7,7).
The sea state membership functions of these terms are:

$$\mu_{gentle}(z)=\begin{cases} 1 & for\ z\leqslant 2 \\ \dfrac{4-z}{3} & for\ 2\leqslant z\leqslant 4 \end{cases};\quad \mu_{med}(z)=\begin{cases} \dfrac{z-2}{3} & for\ 2\leqslant z\leqslant 4 \\ \dfrac{7-z}{3} & for\ 4\leqslant z\leqslant 7 \end{cases};$$

$$\mu_{rough}(z)=\begin{cases} \dfrac{z-4}{3} & for\ 4\leqslant z\leqslant 7 \\ 1 & for\ 7\leqslant \end{cases}$$

The final step is to determine the linguistic variable "radius of guarding ring" on the universal discourse set $U_{\text{GRsize}}=[0, 1]$ and the operating domain of r representing ship size in metres (see Figure 3(d)) by triangular and partial trapezoidal membership functions which specify the terms small (0,0,0,0·5), medium (0,0·5, 0·5,1) and large (0·5,1,1,1). The guarding ring membership functions of these terms are:

$$\mu_{small}(r)=\begin{cases} 1 & for\ r\leqslant 0 \\ \dfrac{0{\cdot}5-r}{0{\cdot}5} & for\ 0\leqslant r\leqslant 0{\cdot}5 \end{cases};\quad \mu_{med}(r)=\begin{cases} \dfrac{r-0}{0{\cdot}5} & for\ 0\leqslant r\leqslant 0{\cdot}5 \\ \dfrac{1-r}{0{\cdot}5} & for\ 0{\cdot}5\leqslant r\leqslant 1 \end{cases};$$

$$\mu_{large}(r)=\begin{cases} \dfrac{r-0{\cdot}5}{0{\cdot}5} & for\ 0{\cdot}5\leqslant r\leqslant 1 \\ 1 & for\ 1\leqslant r \end{cases}$$

In this work, multiple-input single-output (MISO) rules are used for the formulation of the fuzzy guarding ring. To represent a relationship between linguistic variables, fuzzy conditional statements are employed. In this case, the system contains three linguistic variables, x, y and z, such that the value of $L(x)$ is a fuzzy set in A, the value of $V(y)$ is a fuzzy set in B and the value of $S(z)$ is a fuzzy set in C. The MISO IF-THEN rules are of the form:

$$R^i\!:\!IF\ L(x)\ is\ A,\ \ldots,\ AND\ V(y)\ is\ B\ THEN\ S(z)=C_i,\quad i=1,\ 2,\ \ldots,\ n$$

The fuzzy guarding ring model defines the logical implication rules used by experienced navigators and VTS operators. For instance, if ship size is large, speed is high and sea state is rough, then the guarding ring should be large. It is necessary for a mariner to have plenty of time to make a good decision and take the correct action in a collision avoidance scenario. The combination of the value of three linguistic variables has a total of 27 fuzzy rules that are determined by the size of the guarding ring. The components of the fuzzy rules for the guarding ring model are shown in Table 2.

Table 2. Components of the fuzzy rules for the guarding ring

Rule	L	V	S	D
R1	LARGE	FAST	BIG	LARGE
R2	MEDIUM	MIDDLE	MEDIUM	MEDIUM
R3	SMALL	SLOW	SMALL	SMALL
…	…	…	…	…
R25	LARGE	MIDDLE	BIG	LARGE
R26	MEDIUM	SLOW	BIG	MEDIUM
R27	SMALL	MIDDLE	SMALL	SMALL

(L: Length of ship; V: Speed over ground; S: Sea state; D: Guarding ring)

Fuzzy reasoning involves a fuzzy inference engine combining the concepts of fuzzy implication and fuzzy composition. Fuzzy logic principles are used to combine $I=1$ to n rules from a fuzzy rule base into a mapping and from fuzzy input sets to fuzzy output sets (Mendel 2001). Moreover, based on the fuzzy IF-THEN rules in a fuzzy rule base and the compositional rules of inference, Mamdani's minimum fuzzy implication rules can be used. The fuzzy reasoning process is shown in Figure 4.

The most commonly used defuzzification procedure in fuzzy logic control is certainly the centre-of-area approach, also called centre-of-gravity, which in essence is:

$$r_{COA} = \frac{\sum_{j=1}^{n} r_j \mu_D(r_j)}{\sum_{j=1}^{n} \mu_D(r_j)}$$

Where n is the number of quantization levels of the output, r_j is the value of the output at quantization level j, and $\mu(r_j)$ represents its membership value in the output fuzzy set D.

3.3. *Prediction model for vessel collision.* In the proposed model, the collision alert system will be activated if the guarding rings of two target ships start to overlap. Based on three observations that are taken by the time intervals of the faster AIS report of two ships while two guarding rings are overlapping, the alert index function begins operation. If the alert index is increasing and the slope of the radical axis shows little change ($<1°$), then the vessel collision alert system will be started automatically. The length variation of the radical axis is considered as the collision alert index in the VTS system. The value of the collision alert index will decrease if the two approaching ships change course or slow down. Therefore, the value of the alert index is regarded as the reference factor representing collision risk for VTS operators. By utilizing the powerful MGIS capabilities of mapping calculation and spatial analysis, the problems of high computational complexity and large computer memory requirements have been solved.

A ship collision can be defined as occupancy of a specific position by two ships at the same time. Usually, mariners use ARPA data (CPA/TCPA) to determine the collision risk between a target ship and their own ship in relative motion. Once a collision risk is detected, effecting an appropriate navigational operation for collision avoidance becomes very important. However, VTS/ARPA operators do not have

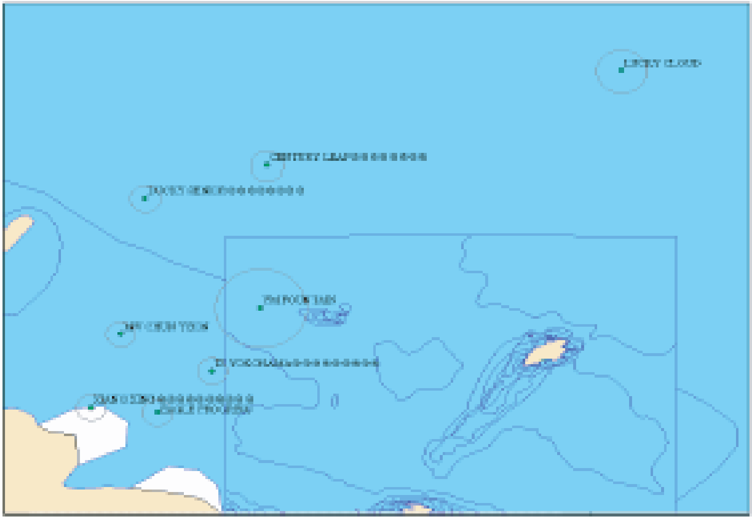

Figure 6. The fuzzy guarding ring model in the VTS/AIS/MGIS integrated system.

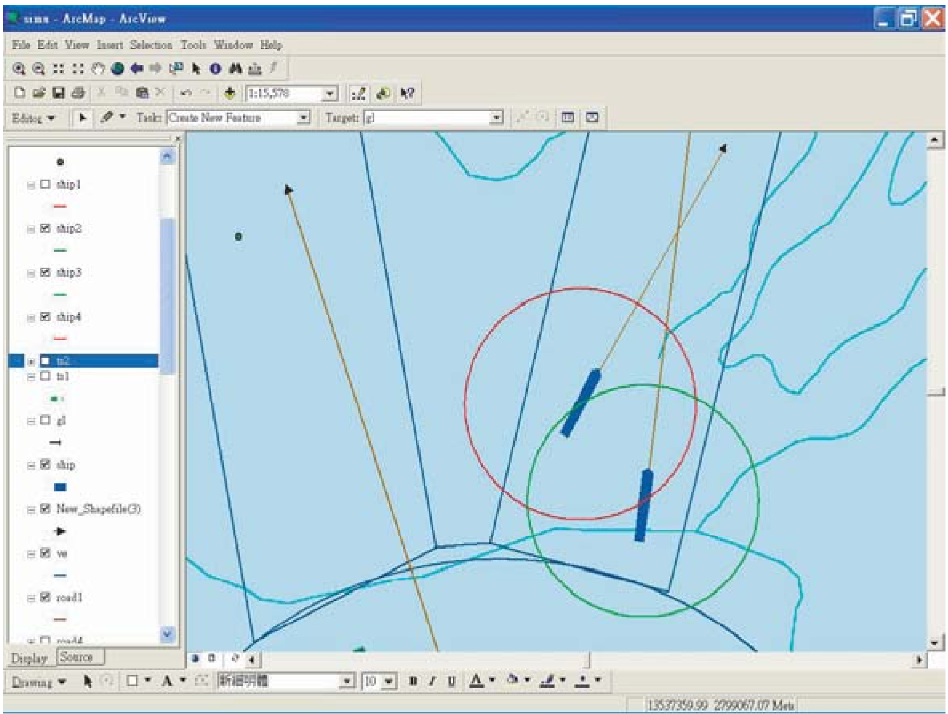

Figure 7. Two overlapping guarding rings of target ships in the alert system.

enough information to make the best choice unless their system is integrated with AIS. Based on information from VTS/AIS/MGIS, the time/position parameters are calculated for the potential collision point and the danger index is calculated in

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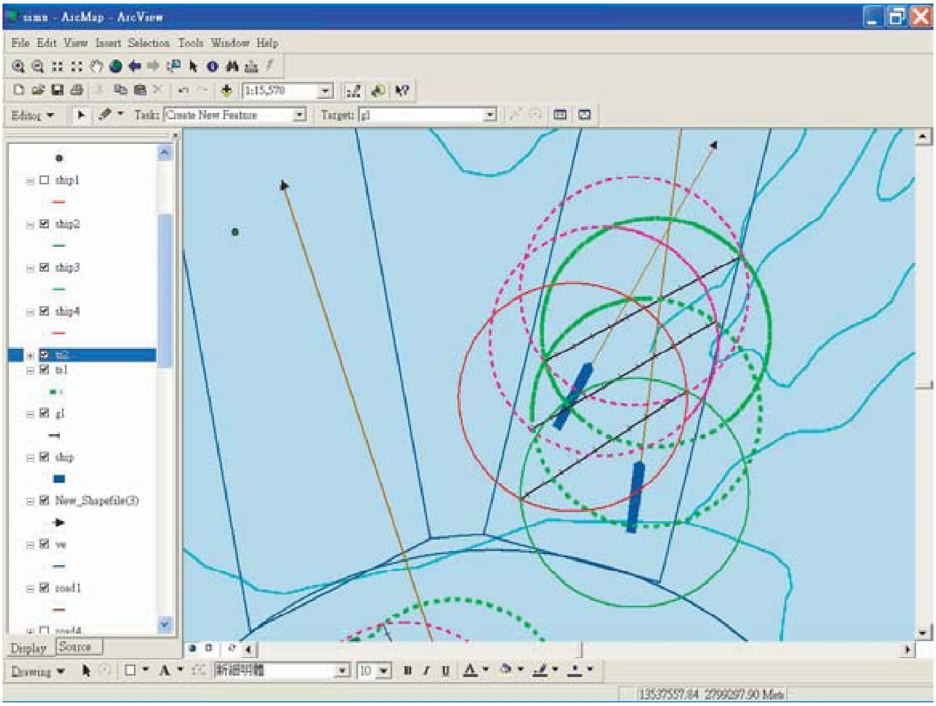
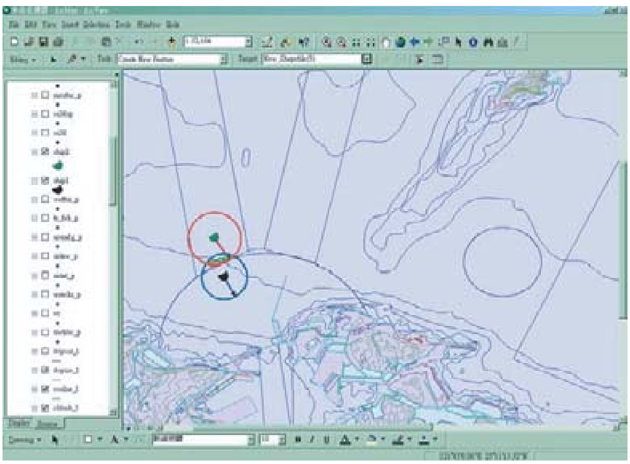


Figure 8. The prediction of course line, collision cross point and geographical relation between two ships in true motion.



(a)

Figure 9(a). The prediction of course line, overtaking and geographical relation between two ships in true motion.

true motion via the fuzzy logic method. Once the system alert starts, the prediction of course line and collision point is shown on the MGIS platform and the danger index is also calculated.

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The danger index is determined by the difference between the safety time interval τ and the discrepancy of collision point Δt for two target ships. The calculation function is:

$$\mu_{danger}(\Delta t)=\begin{cases} 1 & \Delta t=0 \\ 1-2\left(\frac{\Delta t}{\tau}\right)^2 & 0\leqslant \Delta t\leqslant \frac{\tau}{2} \\ 2\left(\frac{\Delta t-\tau}{\tau}\right)^2 & \frac{\tau}{2}\leqslant \Delta t\leqslant \tau \\ 0 & \Delta t\geqslant \tau \end{cases}$$

Where τ is obtained by a fuzzy model of the S function and Δt is the time discrepancy of two observations of the potential collision point. According to the value of the danger index, the two ships maintain a safe condition as long as the discrepancy of collision point Δt for the two target ships is larger than τ. Otherwise, the ships face a risk of collision.

4. SIMULATION. According to the fuzzy guarding ring model, the size of guarding ring is determined by three linguistic variables (fuzzy length, speed and sea state). The mapping diagram between the fuzzy guarding ring (D) and two linguistic variables, fuzzy length (L) and fuzzy speed (V), is calculated using the Matlab fuzzy toolbox. The result on the MGIS platform is shown in Figure 5, where the fuzzy sea state is 2. From the mapping diagram of different sea states, it is apparent that the radius of the guarding ring has a relatively low correlation with sea state. The size of guarding ring in the following simulation is based on the mapping diagram (Chen and Hwang, 1992). In this example, the value of horizontal L and V axes mapping to the value of vertical D axis to determine the size of guarding ring. For instance, the output radius of the fuzzy guarding ring is 0·4722 (calculated by Matlab script file) and the MR is 1·425 nautical miles when the length of ship is 168 metres, speed over ground is 11 knots and sea state is 2.

The proposed VTS/AIS/MGIS integrated system with fuzzy logic control system is constructed using components of Visual C^{++} COM, ArcObjects and ArcMap (Malczewski, 1999). The system has been successfully simulated in Keelung harbour waters on numerous occasions (James, 1986). In these simulations, all vessels have been covered by an AIS base station and under different weather conditions. For example, in May 2005, the size of fuzzy guarding ring is calculated based on fuzzy length (72 m ~ 298 m), fuzzy speed (0 ~ 20 knots) and fuzzy sea state (0 ~ 2) as described in section 3.2. In Figure 6 the bigger size of the guarding ring indicates the more dangerous target ship in the surveillance area in true motion observation. This is different from the traditional ARPA guarding ring that is one size for all and reflects a relative motion observation.

When the guarding rings of two target ships overlap in the alert system as shown in Figure 7, an alert function starts to calculate the length of radical axis by the reporting interval of AIS. The maximum reporting time interval is 3 minutes when a ship is at anchor or moored and not moving faster than 3 knots. Based on three reports while two guarding rings are overlapping as shown in Figure 8, the alert index function begins operation. These three parallel black lines represent the length of radical axis that is calculated by MGIS mapping and spatial modules. Once the alert system starts automatically as described in section 3·3, the predictions of course line and collision point are calculated by MGIS. The calculated danger index [0, 1] is described as the level of the danger criterion and enables the VTS operator to make a proper decision for collision avoidance. It is noted that the danger index for different conditions takes on different values. For the same scenario of two target ships, the danger index is calculated according to two different guarding ring and same collision location. The result of this scenario for overtaking is 0·0725 (see Figure 9(a)), head-on collision is 0·81 (Figure 9 (b)) and crossing collision is 0·7642 (Figure 9(c)). This indicates that the head-on condition presents the highest collision risk.

5. CONCLUSIONS.

In this study, a VTS/AIS/MGIS integrated alert system is proposed to predict the location and time of all potential collisions. It should be noted that our work is based on true motion observation. Thus it provides the VTS operator as a tool for monitoring the motion for all ships to avoid collision accidents in a heavy traffic surveillance area. The proposed fuzzy guarding model offers a new method to reduce collision accidents due to careless mistakes, because collision accidents often happen when approach speed is low in the inner harbour. Furthermore, the integrated system provides a record, which can be used as evidence in case of a marine accident and play back the scenario from beginning to end with time stamps. This information can be considered as marine accident evidence if navigators who ignored the warning advice from the VTS operator noticed in the alert system.

The MGIS platform provides mapping and spatial analysis capability to calculate the collision risk among a large number of ships, which the traditional ARPA is unable to accomplish in a timely fashion. The proposed VTS alert system can be applied to ship-to-ship communications and working platforms at sea as a collision alert system. In a future study, the system will be extended to calculate the timing and angle of rudder required for corrective action, which can be communicated from the VTS operator to the navigator.

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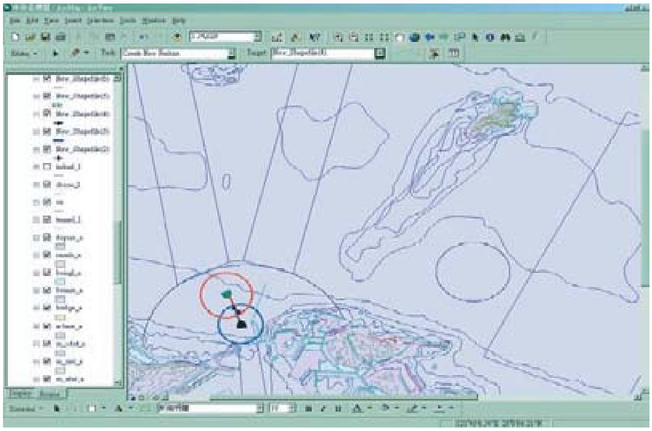
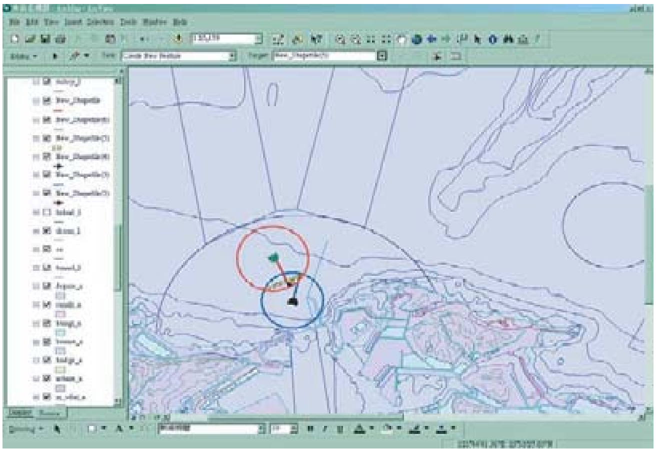


(b)

Figure 9(b). The prediction of course line, head on point and geographical relation between two ships in true motion.



(c)

Figure 9(c). The prediction of course line, collision cross point and geographical relation between two ships in true motion.

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