A Thesis

For the Degree of Master of Science

Collision Avoidance Based on Risk Prediction and Control of Ship

Shu Chen

Department of Computer Engineering

GRADUATE SCHOOL

JEJU NATIONAL UNIVERSITY

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List of abbreviation

ARPA	Automatic Radar Plotting Aids
CR	Collision Risk
ACR	Collision risk for assumed avoiding maneuver
OCR	Collision risk for assumed returning maneuver
VCR	Collision risk for assumed parallel shift maneuver
CPA	Closest Point Approach
DCPA	Distance of closest point approach
DCPA'	Non-dimensionalised DCPA
TCPA	Time of closest point approach
$TCPA_C$	TCPA for CR evaluation
$TCPA_V$	TCPA for VCR evaluation
VCD	Variation of a Compass Direction
C_C	Constant to evaluate $TCPA_C$ taking account of time constant T
C_V	Constant to evaluate $TCPA_V$ taking account of time constant T
GMDSS	Global Maritime Distress & Safety System
GPS	Global Positioning System
ECDIS	Electronic Chart Display and information System
AIS	Automatic Identification System
VTS	Vessel Traffic Service
CR_1	Collision Risk Based on Fuzzy
CR_2	Collision Risk Based on Fuzzy Comprehensive Evaluation
CR_3	Prediction CR_1
CR_4	Prediction CR_2
HCR	Hybrid Collision Risk
HCR^P	Prediction HCR

Abstract

Despite of modern navigation devices, there are still problems in navigation of vessels in waterways due to the geographical structures, disturbances in water, dynamic nature of the sea traffic, and heavily influenced environmental traffic. Even though all vessels are equipped with modern navigation devices, the accidents are reported caused by various reasons mainly by human factor according to investigation. To decrease the accident and increase the safety of sea traffic, researchers proposed an automatic maneuvering system to overcome the human's shortcoming and increase work efficiency.

Simulation system for automatic ship navigation can be a powerful tool for operational planning and design studies of waterways. In such a simulation system the key tasks of autonomous collision risk calculating and collision avoidance are performed by the simulation program itself with no or minimum intervention of a human navigator. This is in many ways similar to automatic navigation systems in that they are designed to carry out autonomous navigation safely and efficiently without the need for human intervention or to offer advice to the navigator regarding the best course of action to take in certain situations.

This thesis presents an effective and practical hybrid collision risk calculation method for finding the collision probability and avoiding the collision for ships in possible collision situations. The algorithm is straightforward to implement and is shown to be effective in automatic ship handling for ships involved in complex navigation situations. We proposed three key task in this thesis; hybrid collision risk calculation at current time, hybrid collision risk prediction at next time and intelligent controller to avoid collisions. Firstly, we proposed a hybrid collision risk calculation method at ship's position using combination of fuzzy and fuzzy comprehensive which is more accurate than existing method by simulation results. Secondly, we extend this hybrid collision risk calculation method to predict the location of ship at next time stamp using Kalman Filter and calculate the hybrid collision risk at next time stamp. Finally, we compared the hybrid collision risk and prediction hybrid collision risk so that the ships collision could be avoided more efficiently and effectively. When the

collision risk is higher in next time stamp the system will send message to the navigator to timely control the ship navigation i.e. angle and speed etc. The navigator must affirm the messages, if there is no affirmation, the system will adopt collision avoidance measures or other rational operations automatically at the critical moment. Additionally, our proposed system also has the decision making capability that how much angle a ship should be deflect to effectively control the ship.

국문초록

현대적인 네이게이션 장치에도 불구하고 지리적 구조, 물속의 장애물, 바다 교통상황의 동적특성, 그리고 교통환경의 영향과 같은 문제가 존재한다. 비록 모든 선박들이 현대적인 네비게이션 장치가 설치 되어져 있지만, 조사에 따르면 인적요소로 인해 발생되는 다양한 원인으로 사고가 보고된다. 해양사고를 감소시키고 해양교통의 안정을 증가시키기 위해 연구에서는 작업의 효율성을 증가시키고 인간의 단점을 극복하기 위해 자동화 작동 시스템을 제안 하였다.

자동화 선박 네비이게이션을 위한 시뮬레이선시스템은 운영계획 및 수로의 설계 연구를 위한 강력한 도구가 될 수 있다. 이러한 시뮬레이션 시스템의 자율적인 충돌위험 계산과 충돌회피의 주요 작업은 인간의 개입을 최소화하여 프로그램 스스로 수행 한다. 유사한 자동 네비게이션 시스템은 인간의 개입없이 안적정이고 효율적인 자동화 네비게이션을 수행 할 수 있도록 설계되어지며, 일정상황에서 사람한테 최적의 코스를 제공한다.

이 논문은 충돌가능한 상황에서 선박의 충돌 가능성을 찾고 충돌을 회피하기 위한 효율적이고 실용적인 혼합 위험도 계산 방법을 제시하고 있다. 이 알고리즘은 구현이 간단하고 복잡한 향해 상황에서 선박을 효율적이고 자동으로 다뤄준다. 자동화선박 네비게이션의 세 가지 주요 제안은 현재 시간의 혼합 충돌 위험도 계산, 다음 시간의 혼합 위험도 예측과 충돌을 피하기 위한 선박 제어가 있다. 첫 번째 우리는 선박 위치 기반의 혼합 위험도 계산 방법을 제시한다. 이 방법은 퍼지와 퍼지 종합 평가 방법을 결합하여 기존의 충돌 위험도 계산 방법보다 정확도 가 더 높다. 두 번째 이 혼합 위험도 계산을 확장하고 칼만 필터를 사용해서 다음시간 스템프에 선박의 위치를 예측하고 다음 시간 스템프에

혼합 충돌 위험도를 계산한다. 마지막으로 현재 시간의 혼합 위험도와 다음 시간의 혼합 위험도를 비교해서 충돌을 미리 피할 수 있도록 한다. 다음 시간의 위험도가 높으면 시스템은 항해자에게 적시에 선박을 제어하기 위한 속도와 각도등의 메시지를 보내준다. 항해자는 이 메시지를 확인해야 하고 만약에 항해자의 반응이 없으면 시스템은 중요한 순간에 자동으로 충돌 방지 조치나 기타 합리적인 운영을 채택하게 될 것이다. 또한, 제안된 시스템은 얼마나 많은 각도로 선박의 방향을 효율적으로 제어할지 결정할 수 있는 능력이 있다.

1. Introduction

1.1. Background and objective

With the development of marine traffic and world's growing economic needs in recent years, the ship amounts in the ocean is increasing rapidly, so the environment of navigation has great change and this make the maneuvering of ship be more difficult. Consequently, the increasing marine traffic has been emerged as an important issue. Although ARPA (Automatic Radar Plotting Aids), GMDSS (Global Maritime Distress & Safety System), GPS (Global Positioning System), ECDIS (Electronic Chart Display and information System), AIS (Automatic Identification System) and VTS (Vessel Traffic Service) etc. advanced navigational auxiliary equipment have been applied in navigation, but it's hard for the VTS operators to manage rapidly growing traffic with conventional plotting equipments and to give traffic instructions to the vessel's captain in short time. Moreover, it's nearly unfeasible to upgrade the entire VTS centre with latest automatic equipments because of their high cost. Because of these challenges, numbers of accidents have occurred recently which results the human casualties. Due to the sensitivity of issue, many researchers are devoted to marine system issues and tried to develop better collision avoidance method to reduce the possibility of vessel collision accidents by providing early-warning solutions. The research data shows that eighty percents of marine accidents induce by human factor (Guedes Soares & Teixeira 2001, Gaarder et al.1997). To increase the safety of navigation and decrease the accident, more and more researchers try to develop a more effective decision making system is similar to the human brain that can calculate the collision risk between vessel and based on collision risk make the best decision in special situation to prevent the marine accidents and send the warning and avoidance message to mariner. Due to long and hard journey in sea, sometimes mariners are tired, so even they received the warning messages it is too late after they take actions to prevent collision. State of the art techniques considers the collision risk at the ship's position which is based on the all the ship's in the surrounding of that ship (Q.Xu & X. Meng 2010). The problem in these approaches is that accurate collision risk calculation is not always possible due the dynamic nature of the sea traffic, weather, and water behavior. Therefore there is a dire need of a system which calculates the collision risk at the ship's path considering the dynamic nature of sea traffic. Let's consider a situation, we want to develop a more intelligent decision making system that can not only detect the collision risk but also make the right decision to prevent marine accidents. And all this process should be automatic. This system calculate the collision risk of current time and also predict the collision risk of next time, if the collision risk of next time step is higher than current time, the system will take action in advanced and prevent the collision accident. This system accuracy will higher than previous researcher.

1.2. Content of research

In this work, we propose an intelligent vessel collision risk assessment system that be shown in Figure 1.1. We combine the theories of fuzzy, fuzzy comprehensive evaluation and the conventional risk calculation techniques to calculate the hybrid collision risk between vessels. Furthermore, we predict the hybrid collision risk of next time between the vessels using Kalman Filter. Moreover, we compare the hybrid collision risk of current time and next time, if the hybrid collision of next time is bigger than hybrid collision risk at current time, which means we need to tack action to reduce the collision risk by change the angle or speed of vessel.

We divided our proposed system in three functional modules as be shown in figure 1.1. The first module is the collision risk calculation module which calculates the collision risk between ships at current time based on combined fuzzy and membership functions. The second module is collision risk prediction module which predicts the collision risk between ships at next time using Kalman Filter. The last module is ship control module which will take action to control the ship automatic based on collision risk comparing results between current time and next time.

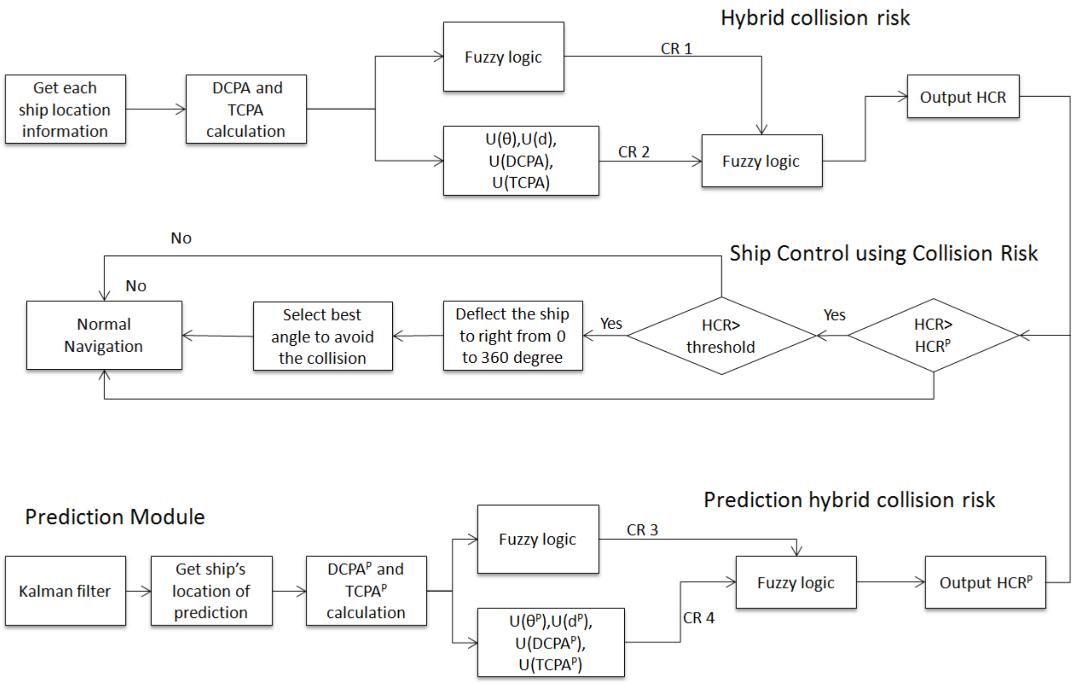

Figure 1.1: Conceptual diagram of proposed system

1.3. Thesis outline

The outline of this thesis is organized as follows: Chapter 1 describes the Background of vessel collision risk and objectives. Chapter 2 provides the previous researches related to collision risk calculation method. Chapter 3 proposes the hybrid collision risk calculation method of current time based on fuzzy logic and fuzzy comprehensive evaluation and designed to test the validity of the proposed scheme and simulation results. Chapter 4 proposes the hybrid collision risk prediction of next time using Kalman Filter and simulation and performance. Chapter 5 proposes the vessel Control method based on hybrid collision risk comparison of current time and next time. Chapter 6 presents at last conclusions of the findings in this research.

2. Related Works

2.1. Collision risk

There are many collision risk indices proposed by researchers (Kazuhiko Hasegawa & Junji Fukuto, 2012). Ship domain concept is probably the first concept treating it (FUJII, Y, et al 1996& FUJII, Y 1969). In this study CR is used. CR is the collision risk defined by DCPA and TCPA using fuzzy reasoning (HASEGAWA, K 1987). Later the definition of CR is somewhat modified and now the following definition is used in (Kazuhiko Hasegawa 2012). For assessing collision risk in normal condition, CR defined by TCPA and DCPA' (eq. (3)) is used. For determining avoiding action, ACR is used to check the collision risk of the assumed avoiding action. In this case, following modified TCPA is used for calculating ACR considering individual ship maneuverability, especially for large ships.

$$TCPA_C = TCPA - C_C T \tag{1}$$

For determining the timing to take returning to the original path, VCR and OCR are used to check the collision risk of assumed returning action. In this case of following modified TCPA is used for calculating VCR and OCR considering rapid turn of small ships.

$$TCPA_V = TCPA - C_V / T \tag{2}$$

Where C_C and C_V are constants and T is the time constant (of Nomoto's equation) of the subject ship. In the simulation, C_C =2 and C_V =1000 are used based on some simulation results. These modifications are reflecting the difference of course changing ability roughly estimated from the time constant T.

DCPA is non-dimensionalised using longer ship’s length of two ships encountered.

$$DCPA' = DCPA / \max(L_O, L_T) \quad (3)$$

Both $TCPA_C$, $TCPA_V$ and DCPA' are defined by 8 and 5 linguistic variables using membership functions as shown in figures 2.1 and 2.2 respectively, which are determined by authors' previous researches on experts knowledge and experience and both maximum values (360 and 7.2 for open sea respectively) can be modified based on the gaming area, or users can tune them as they like. Collision risk CR is defined by 8 linguistic variables and membership functions as shown in figure 2.3.

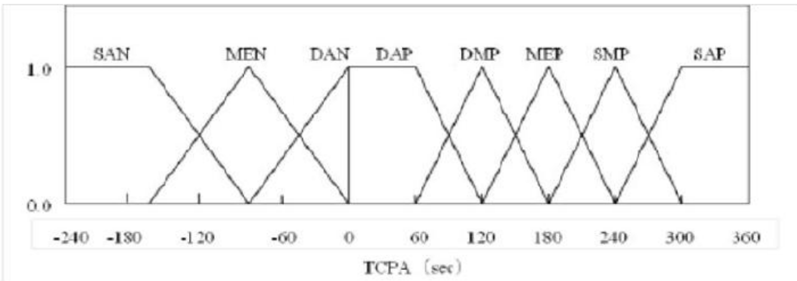

Figure 2.1: Memebership function for $TCPA_C$ or $TCPA_V$

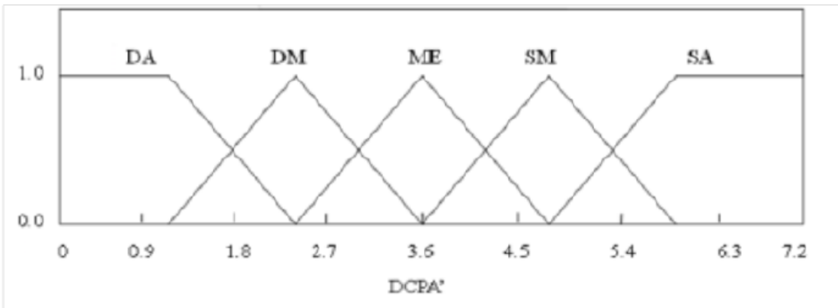

Figure 2.2: Membership function for DCPA'

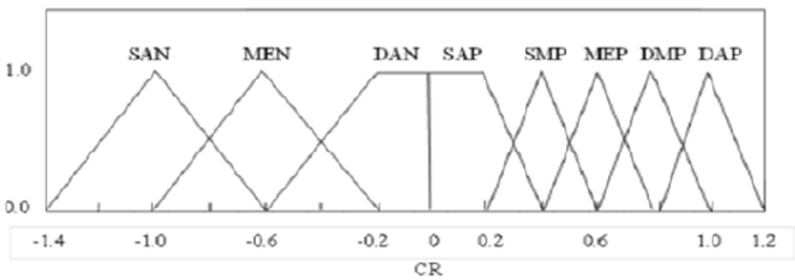

Figure 2.3: Membership function for CR

The reasoning fuzzy table to determine CR is provided using $TCPA_C$ and DCPA' as shown in table 2.1. CR is thus defined between -1 and 1 and it is positive before passing CPA and negative after passing CPA. The absolute value is proportional to the collision risk.

Table 2.1: Fuzzy reasoning table for CR

		TCPA							
		SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
DCPA'	DA	SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
	DM	SAN	SAN	MEN	DMP	MEP	SMP	SAP	SAP
	ME	SAN	SAN	SAN	MEP	SMP	SAP	SAP	SAP
	SM	SAN	SAN	SAN	SMP	SAP	SAP	SAP	SAP
	SA	SAN	SAN	SAN	SAP	SAP	SAP	SAP	SAP

2.2. Assessment of collision risk and actions

The approach to assessing the collision risk is based on using a knowledge-based system (Ming-Cheng Tsou & Chao- Kuang Hsueh 2010). The knowledge-based system embodies collision avoidance techniques by using the 1972 international rules for collision avoidance (COLREGS) as the key information. The calculations for collision avoidance path planning are only executed when the collision avoidance conditions in the knowledge base have been satisfied. According to the combined results from analysis of COLREGS, navigation practices and automated collision avoidance methods, the encounter situation covered by COLREGS is divided into three types, where each type in turn is divided into subdivisions. The three main types of encounter situation are discussed below:

(1) **Head-On:** target ship approaching from E region in figure 2.4. The own ship and target ship are approaching each other on reciprocal or near-reciprocal courses. Both ships should alter their courses to starboard so that each shall pass on the port side of the other.

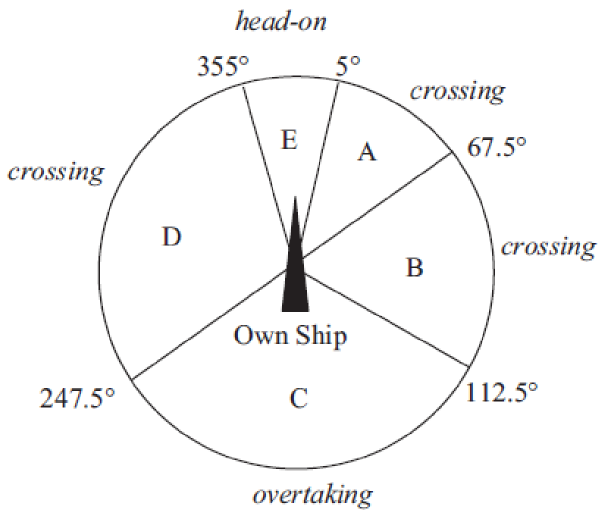

Figure 2.4: Chart divisions show states encountered of ship

(2) **Crossing:** target ship approaching from A, B or D region in figure 2.4. The own ship and target ship are crossing each others' intended paths and so there is a risk of collision. The own ship is the stand-on ship and keeps its course and speed when the target ship is crossing from port to starboard of the home ship (D region in figure 2.4). If the target ship fails to take action, the home ship itself should substantially alter its course. The home ship is the give-way ship when the target ship is crossing from starboard to port of the home ship (A region in figure 2.4). If there is sufficient sea area, the own ship can alter its course substantially to starboard and cross from astern of the target. For the ship from B region, if its relative angle with the own ship is great, a left turn can be taken to avoid collision.

(3) **Overtaking:** target ship approaching from region C in figure 2.4. A ship shall be deemed to be overtaking when another ship approaches from a direction more than 22.5 degrees abaft her beam. If a home ship is overtaking a target ship, the target ship is the no-deviation ship and should keep its course and speed. If the own ship is on the starboard quarter of the target ship, the own ship should alter its course to starboard. If the home ship is

on the port quarter of the target ship, the home ship should alter its course to port.

2.3 Existing collision risk calculation method using fuzzy comprehensive evaluation

The security of maritime traffic is a significant part of intelligent maritime traffic. It can reduce to ship maneuvering and collision avoidance by macroscopic. Eighty percents of marine accident induce by human factor from research data (Guedes Soares & Teixeira 2001, Gaarder et al.1997). So some researches about intelligent computer evaluation system to reduce the accident of human caused have emerged. Intelligent evaluation system of ship maneuvering can calculate the status of ship and getting the data of ship around, and then adopt fuzzy comprehensive evaluation method to calculate the collision risk and evaluate the operation of navigator. If it has danger of collision risk or the navigator adopts irrational operation scheme by calculating, the system will send message to the navigator. The navigator must affirm the messages, if there is not affirmation, the system will adopt collision avoidance measures or other rational operations automatically at the critical moment.

2.2.1 The structure of intelligent evaluation system

The evaluation system consist of many models, including target ship identification (Q.Xu & X.Meng 2012), speculation and prediction of encounter status, real evaluation of operation, auto-collision avoidance strategy and risk warning model etc. We can see from figure 2.5, the evaluation system and operation of navigator form a closed-loop control system. The system will evaluate the performance of operation, and send out corresponding signals. In this way it can make up the disadvantage of none precision calculation of human, cut down the probability of human fault occurrence, and secondly make use of human's high adaptability sufficiently.

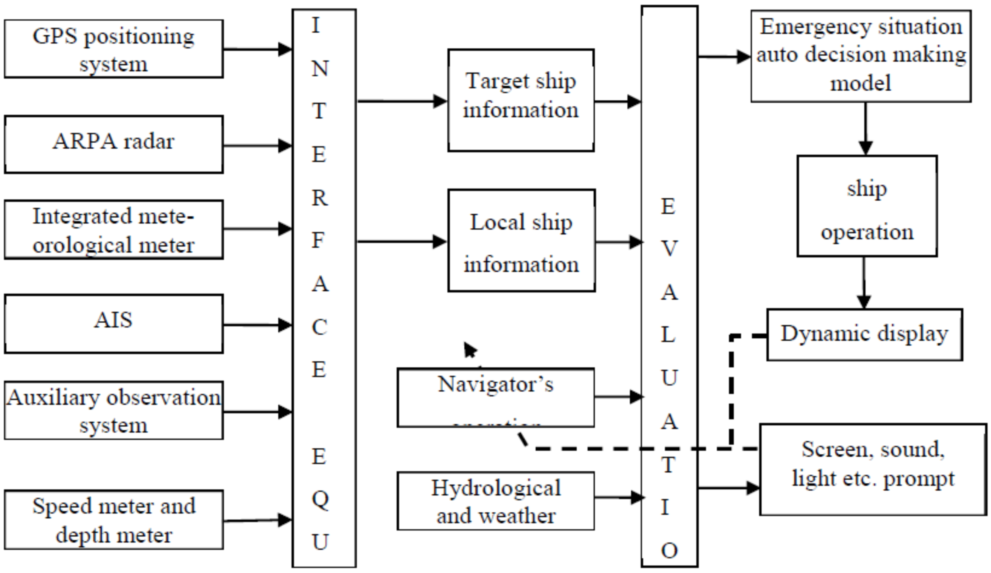

Figure 2.5: Diagram of evaluation system of ship maneuvering

2.2.2 Collision risk calculation method

Ship collision risk calculation is one of the most important parts in the system. The quantification of collision risk experience several stages basically (WU Zhao-lin & ZHENG Zhong-yi 2001). The first one is traffic flow theory which use ship collision rate, encounter rate, collision probability to evaluate the collision risk for special water area. The second is ship domain and arena which is based on human praxiology and psychology. (Fuji & Tanaka 1971), (Goodwin 1975) etc. who use this to calculate collision risk. In the third stage, people have considered the DCPA (Distance at Closest Point of Approach) and TCPA (Time at Closest Point of Approach) in calculation, like (Davis et al. 1980). In the fourth stage, combine DCPA and TCPA, adopt weighting method to calculate collision risk at the beginning (Kearon 1979, Imazu& koyama 1984). This method exist obvious disadvantage that DCPA and TCPA are two different variables. Then people adopt fuzzy theory to combine DCPA and TCPA. At present mostly research are based on the artificial intelligent technology as fuzzy theory, expert system, neural network to calculate the collision risk (LI Li-na 2006). This section adopts fuzzy compressive evaluation to calculate collision risk. The comprehensive evaluation result can be used as subjective evaluation, and also can be as objective one. Furthermore, system security is a progressively process. We can get perfect result through assessing the subordination of the factors. So we don't use the weighting of DCPA and TCPA to calculate collision risk, they applied fuzzy comprehensive evaluation in it. There are many factors effecting CR. We only consider the major factors here, the distance between target ship and local ship d, the position of target ship θ, DCPA and TCPA. Collision Risk is:

$$CR = [w_d u_d + w_\theta u_\theta + w_{dCPA} u_{dCPA} + w_{tCPA} u_{tCPA}] \quad (4)$$

2.4 Existing collision risk calculation method using fuzzy

Due to brisk industrial growth, the marine traffic has become an imperative subject in the open sea nowadays (Ahmad C.Bukhari & Inara Tusseyeva 2013). The crew inside the vehicle traffic service (VTS) centre is facing challenging issues on account of continuous growth in vessel number. Currently, most of VTS centers' are using the ARPA RADAR based conventional vehicle traffic management system and VTS staff has to carry out most of the things manually to guide the ship's captain properly. Therefore, there is a strong impetus in the field of ocean engineering to develop a smart system which can take the data from

RADAR and autonomously manipulate it, to calculate the degree of collision risk among all vessels from the VTS centre. Later on, the traffic management officer utilizes this information for intelligent decision making. In the past, several researchers have addressed this issue to facilities the VTS crew and captain of the ship but mostly, their research work was for academic purposes and could not get popularity because of extra manual workload. Our proposed vessel collision risk assessment system is an intelligent solution which is based on fuzzy inference system and has the ability to solve the said issues. We calculated the DCPA, TCPA, bearing and VCD among all vessels ships from the VTS centre by using conventional marine equipments and exploited the extracted information to calculate and display the degree of collision risk among all vessels. Furthermore, we developed the RADAR filtration algorithm which helps the VTS officer to gauge out the degree of collision risk around a particular ship. To authenticate the validity and to monitor the performance efficiency, we developed RADAR operated intelligent software which directly gets the required data from RADAR and displays the vessels list based on their degree of collision severity. The laboratory experiments confirm the validity of the proposed system.

(Ahmad C.Bukhari & Inara Tusseyeva 2013) divided their proposed system in three functional layers as shown in figure 2.6. The first layer is the input layer which calculates or acquires the input parameters required for the associated modules to calculate the collision risk. We introduced a mechanism to calculate the DCPA, TCPA and VCD by using conventional VTS equipments in the first layer. The second layer (fuzzy inference layer) is the core layer of our system; it is responsible to apply fuzzy rules and to generate the intelligent decision on the behalf of this. The results of this layer are further forwarded to the display layer which is specially designed to format and present the results in human readable format. By starting the simulator, the intelligent algorithm automatically triggers the radar scanning function of intelligent algorithm. The radar scanning function inspects for all of the vessels which comes under the scanning range and stores the data in arrays and in log files for further manipulation (Yong, 2009). ARPA radar can display the information about: bearing, range, speed, CPA and etc. Since, we have been using the simple radar here which can only calculate and display limited features about marine traffic.

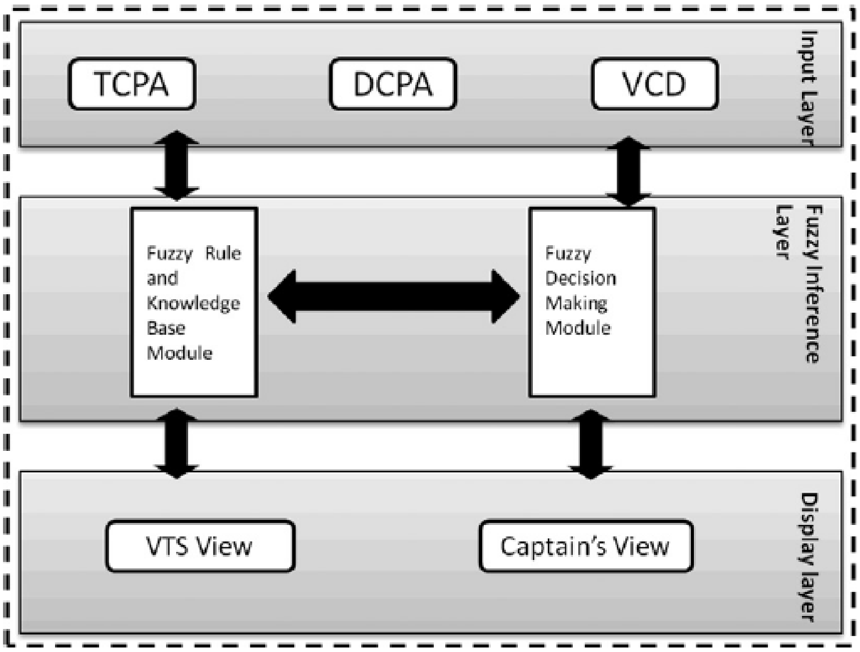

Figure 2.6: Multi-vessel collision risk assessment system architecture

Figure 2.7 below is displaying the basic architecture of fuzzy logic based controller (Ren, Mou, Yan, & Zhang, 2011).

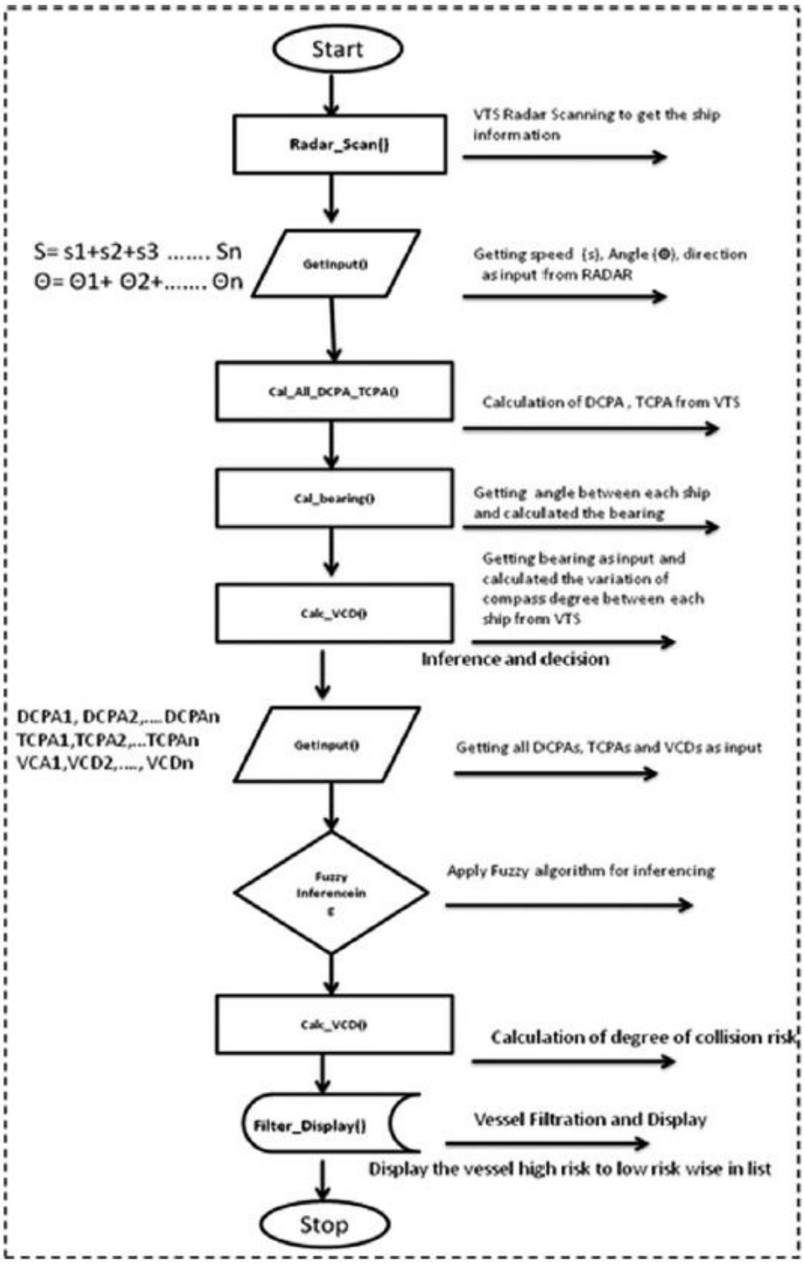

Figure 2.7: Flowchart calculation of collision risk among vessel from VTS

There are five linguistic values for the variables VCD, TCPA and DCPA (Smierzchalski & Michalewicz, 2000):

{Positive small, Positive medium small, Positive Big, Negative small, Negative medium small, Negative Big, Positive Medium Big}

The fuzzy reasoning rule tables, in case when VCD is PS, PMS, PM, PMB and PB. The figure 2.8 shows the graphical user interface of the developed simulator (Okazaki, Koike, Hirai, & Kayano, 2010). We segregated the displayer layer into four sub-modules which are ship statistics module, calculation of DCPA, TCPA and VCD module, collision risk list module and filtration module as highlighted in figure 2.9.

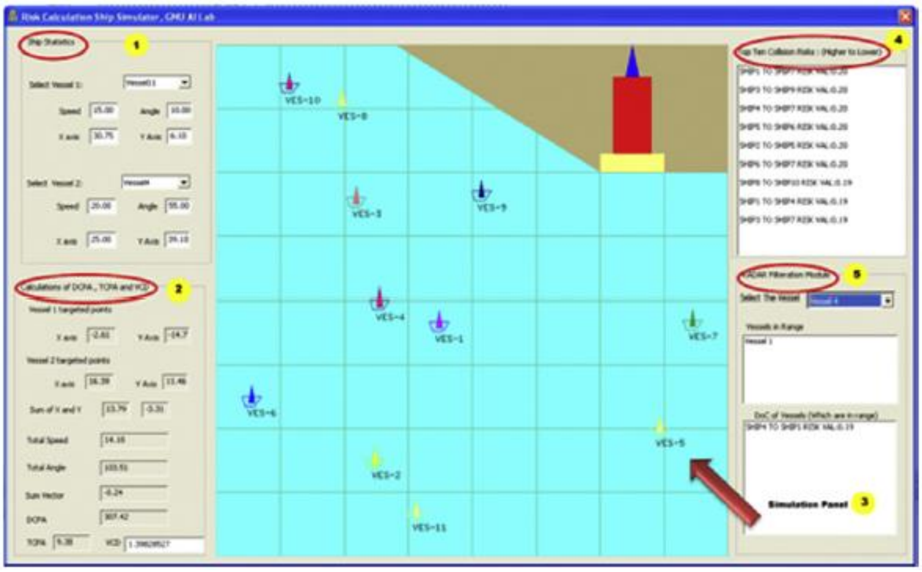

Figure 2.8: Screenshot of the vessels collision assessment simulator

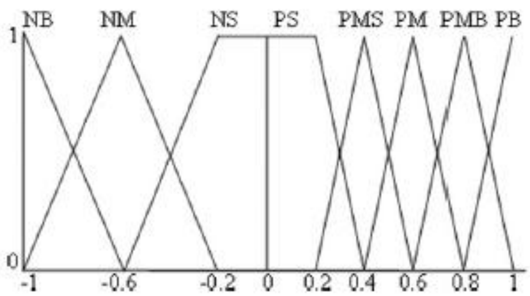

Figure 2.9: Membership function of degree of collision risk

3. Hybrid collision risk calculation method

Ship collision risk calculation is one of the most important parts in the system. Basically the quantification of collision risk experience several stages (Wu Zhao-lin & Zheng Zhong-yi 2001). The first one is traffic flow theory which use ship collision rate, collision probability to evaluate the collision risk for special water area. The second is ship domain and arena which is based on human praxiology and psychology. (Fuji & Tanaka 1971), (Goodwin 1975) etc. who use this to calculate collision risk. In the third stage, people have considered the DCPA and TCPA in calculation, like (Davis et al. 1980). In the fourth stage, combine DCPA and TCPA, adopt weighting method to calculate collision risk at the beginning (Kearon 1979, Imazu & koyama 1984). This method exist obvious disadvantage that DCPA and TCPA are two different variables. Then people adopt fuzzy theory to combine DCPA and TCPA. At present mostly research are based on the artificial intelligent technology as fuzzy theory, expert system, neural network to calculate the collision risk (Li Li-na 2006).

In this chapter, we mainly present the first module of proposed system that shown in figure 3.1. The first module is the hybrid collision risk calculation module which calculates the collision risk between ships at current time based on combination of fuzzy and fuzzy comprehensive evaluation. In this module, firstly we present a mechanism to calculate the DCPA and TCPA between each ship using the state information of ships that received from radar. Secondly, the CR_1 will be calculating based on fuzzy after input the DCPA and TCPA. Meanwhile, the CR_2 be calculating based on the membership functions of DCPA, TCPA, d (distance between ships) and navigation angle of target ship. Thirdly, the CR_1 and CR_2 will be input to fuzzy system again and get the hybrid collision risk at current time.

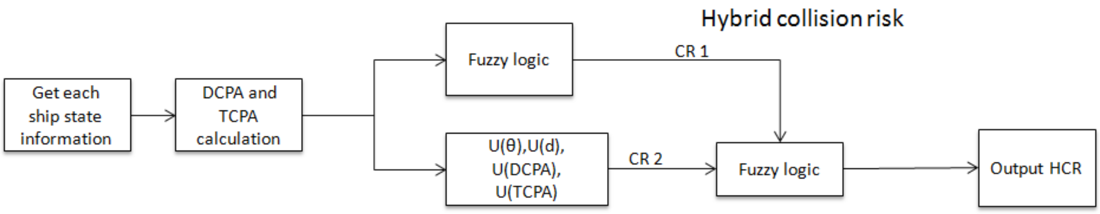

Figure 3.1: Hybrid collision risk calculation module of proposed system

3.1 Collision risk calculation method based on fuzzy

3.1.1 DCPA and TCPA calculation method

In this section we introduce the collision risk calculation module that will calculate the collision risk at current time. Figure 3.2 shows the flowchart diagram of collision risk calculation at current time. Firstly, we will obtain the state information of each ship by the VTS Radar scanning at current time. Then the DCPA and TCPA will be calculated based on ship's position and navigation angle. After that input the DCPA and TCPA to fuzzy logic system calculate the CR_1 and CR_2 will be calculated based on membership functions of navigation angle, distance between two ships, DCPA and TCPA. At last, the hybrid collision risk of current time will be calculated using fuzzy again.

The figure 3.3 displays the two vessels, labeled as ship *O* and ship *T*, both the vessels are moving with different speed and course. The bold red arrow in the figure is indicating the distance to the closest point of approach (DCPA) between ship *O* and ship *T*. To precisely measure the degree of collision risk among the vessels.

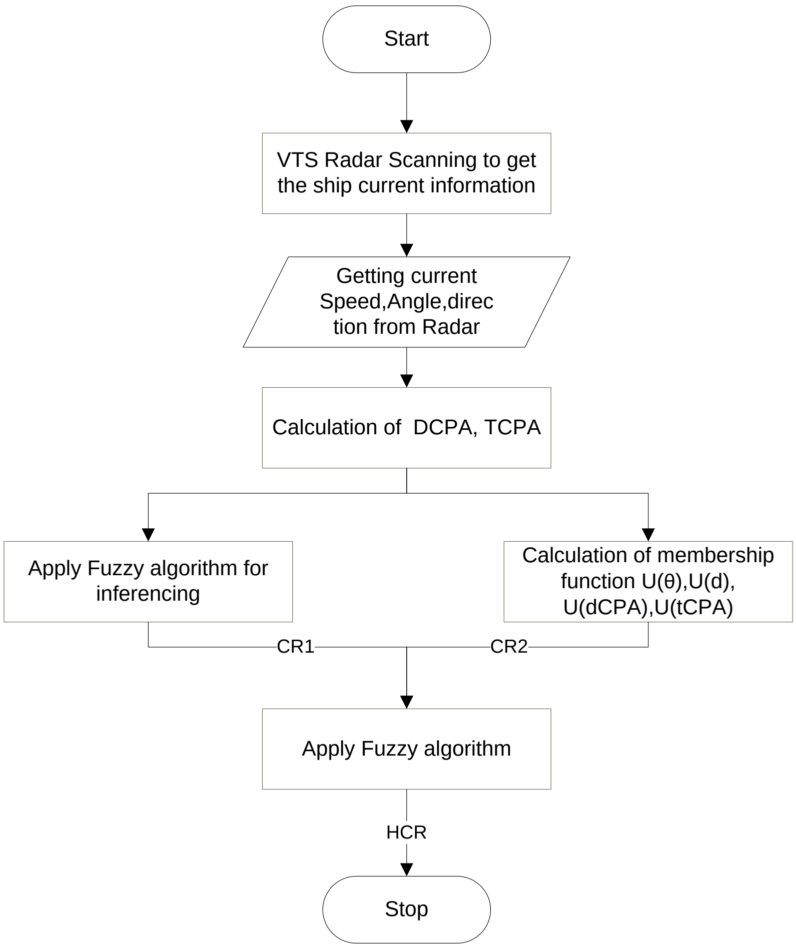

Figure 3.2: Flowchart of hybrid collision risk calculation

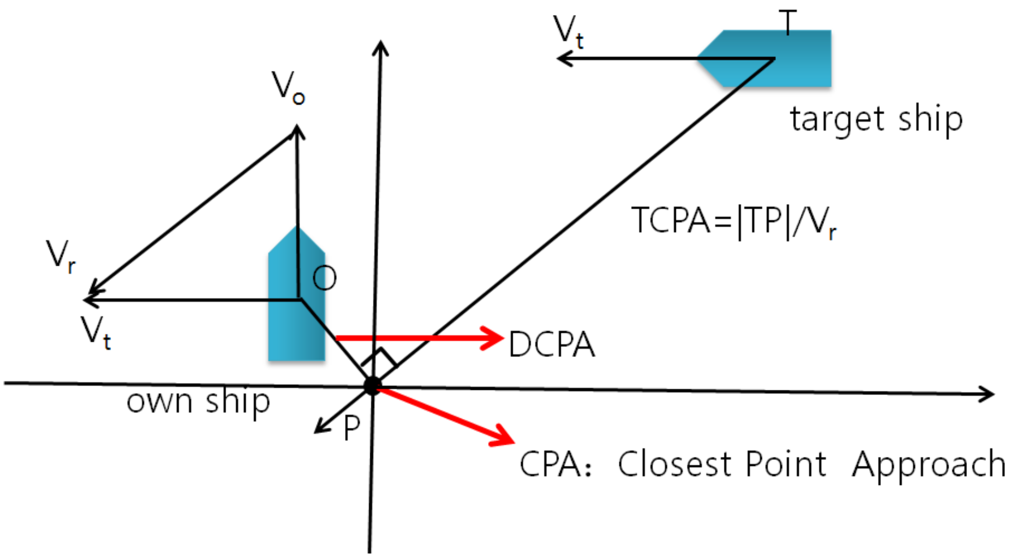

Figure 3.3: Diagram of DCPA and TCPA concept

The figure 3.4 is demonstrates the whole scenario. The vessel $O(x_O, y_O)$ is maneuvering towards the Northeast while the vessel $T(x_T, y_T)$ is maneuvering towards the Northwest. Both the vessels are moving with different speed (V_O, V_T) and course (θ_O, θ_T). To find the DCPA and TCPA between vessel *O* and *T*, we calculate the relative speed of own ship to the target ship using equation (5). The relative speed is depicted in figure 3.4. The figure 3.4 shows that a perpendicular line is drawn on the own ship from the parallel vector of the target ship. The distance between the parallel vector of target ship's direction and the own ship's position is DCPA as calculated by equation (9).

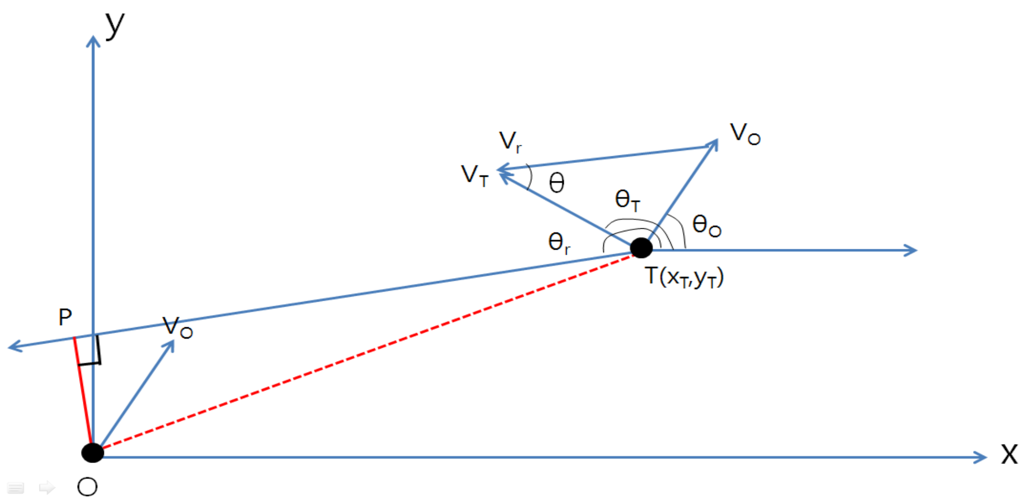

Figure 3.4: Scenario diagram of DCPA and TCPA Calculation

We defined relative speed to target ship measured from own ship is V_r and is calculated as:

$$V_r = \sqrt{V_O{}^2 + V_T{}^2 - 2|V_O \cdot V_T|\cos(\theta_T - \theta_O)} \quad (5)$$

We defined the slope intercept form of line *TP* is $Y - y_T = k(X - x_T)$ which parallel with relative speed and start from target ship's position.

$$k = \tan\theta_r \quad (6)$$

$$\theta_r = \theta_T + \theta \quad (7)$$

$$\theta = \arccos\left(\frac{V_r{}^2 + V_T{}^2 - V_O{}^2}{2V_r \cdot V_T}\right) \quad (8)$$

Where *k* is the slope of the line *TP*, θ_r is the relative angle and θ is the angle between relative velocity V_r and target velocity of current time.

Mathematically, at current time, the DCPA between vessels *O* and *T* from VTS can be calculated by using the following equations.

$$dCPA = |OP| = \frac{|y_T - x_T \tan\theta_r|}{\sqrt{\tan^2\theta_r + 1}} \tag{9}$$

Mathematically, at current time, the TCPA between vessels *O* and *T* from VTS can be calculated by using the following equations.

$$|TP| = \sqrt{|OT|^2 - |OP|^2} = \sqrt{(x_T{}^2 + y_T{}^2) - dCPA^2} \tag{10}$$

Where OT is the distance between Own ship and Target Ship, *OP* is the perpendicular line from Own ship to line *TP* at current time.

$$tCPA = \frac{|TP|}{V_r} = \frac{\sqrt{(x_T{}^2 + y_T{}^2) - dCPA^2}}{V_r} \tag{11}$$

3.1.2 Fuzzy set theory

Fuzzy set theory was introduced by Lotfi Zadiah in 1965 (Zadeh, 1965) to deal with vague and imprecise concepts. In classical set theory, elements either belong to a particular set or not. The concept of partial membership does not exist in classical set theory. However, in fuzzy set theory the association of an element with a particular set lies between 0 and 1; which is called its degree of association or membership degree. In our daily life, we find many vague statements like hot water, cold weather, dark night, high danger etc. We cannot quantify exactly about the severity of the danger or hotness. The fuzzy set theory adds generalization concept in classical set theory and makes it diverse enough to represent imprecise boundaries like hot, tall, low speed, high risk etc. A fuzzy set can be defined as (Yong, 2009; Zadeh, 1965).

Definition 1. A fuzzy set 'FS' over the universe of discourse 'Y' can be defined by its membership function μ_{FS} which maps element 'y' to values between[0,1].

$$\mu_{\mathrm{FS}} : Y \rightarrow [0,1] \tag{12}$$

Here $y \in Y$ and $\mu_{\mathrm{FS}}(y)$ provides the degree of membership by which y belongs to Y. y is considered as full member of Y if $\mu_{\mathrm{FS}}(y) = 1$ and is considered as partial if $\mu_{\mathrm{FS}}(y)$ is between '0' and 1 say '0.57'. If Y is continuous then S can be written as:

$$\breve{S} = \int_{y} \mu s() / y \tag{13}$$

A fuzzy set $\breve{S}$ over the universe of discourse Y is organized into ordered of set pairs:

$$\breve{S} = \{(y, \mu s(y)) \mid y \in Y\} \tag{14}$$

Definition 2. Let X and Y are the two universe discourse, a fuzzy relation R(x, y) is a set of product space $X * Y$ in a membership function.

$$R(x, y) = \{(x, y), \mu_R(X, Y) \mid (X, Y) \mid \in X * Y\} \tag{15}$$

So in compliance with fuzzy set theory, suppose x and y are fuzzy sets in the product space $X * Y$. Fuzzy relation represents a degree of presence or absence, interaction or inter-connectedness between the elements of two crisp sets (Ahmad& Yong, 2012).

3.1.3 Fuzzy rules based on decision making module

A fuzzy inference system is a popular framework that utilizes the fuzzy set theory to map the inputs to the outputs. It is a core of a fuzzy logic control system. It has been applied widely by the researchers in a variety of fields such as data classification, robotics, expert systems, pattern recognition etc. Due to its effectiveness in multidisciplinary fields the fuzzy inference system is known by numerous other names like fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, or simply (and ambiguously) fuzzy systems. If we analyze the fuzzy inference system, it can be subdivided into three main components: rule base, database or dictionary and reasoning mechanism (Jianghua & Guang, 2006) interesting to note that, the fuzzy inference system takes the input either in fuzzy values format or a crisp format but the output is always being in fuzzy format. Sometimes the output requires treatment before utilizing it for decision purpose, especially when we are working on a controller.

We first have to defuzzify the output before its utilization. The figure 3.5 below is displaying the basic architecture of fuzzy logic based controller (Ren, Mou, Yan, & Zhang, 2011).

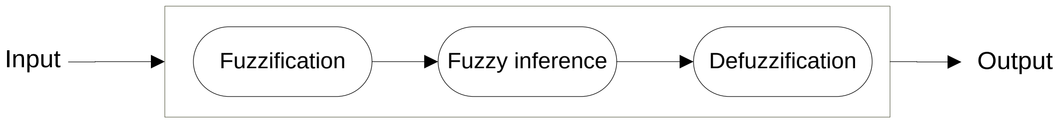

Figure 3.5: A fuzzy logic Controller

The process of fuzzy inference involves all of the pieces that are described in the previous sections: Membership Functions, Logical Operations, and If-Then Rules. There are two widely used methods for fuzzy inference systems: Mamdani and Sudeno. The input for the fuzzy logic control systems is crisp data (intervals or linguistic values). The Mamdani fuzzy inference system is very popular and considered as a first choice of controller researchers.

It was developed to control a steam engine and boiler combination of asset of linguistic rules obtained from experienced human operators in 1977. The details of the Mamdani fuzzy inference system can be found in Mamdani and Assilian (1999). There are five kinds of defuzzification processes; among them are smallest of maximum, largest of maximum, centroid of the area, the bisector of the area and mean of maximum.

The inference module consists of basic rules like if a = max and b = max then c = max which is called Max-Criterion method. This method selects a random value from the set of maximum elements. Linguistic fuzzy model of Mamdani type is built on the fuzzy linguistic rules with linguistic variables. We formed the fuzzy reasoning rule tables to express the associated constraints with vessel collision system.

The system has the type of multi-input-multi-output system; the reason is that the antecedents and consequences of rules are expressed in several linguistic variables. This kind of system includes the set of rules which has the following form:

R1 : IF x is A1 AND y is B1 THEN Z is C1

R2 : IF x is A2 AND y is B2 THEN Z is C2

R3 : IF x is A3 AND y is B3 THEN Z is C3

Rn : IF x is An AND y is Bn THEN Z is Cn

Where x and y are the process state variables, z is the control variable, Ai, Bi and Ci are linguistic values of the linguistic variables x, y and z in the universes of discourse U, V and W, respectively.

Figure 3.6 shows the flowchart of CR_1 calculation among ships. We computed the DCPA and TCPA in the section 3.1.1. Here, we input the DCPA and TCPA to fuzzy logic and output the CR_1.

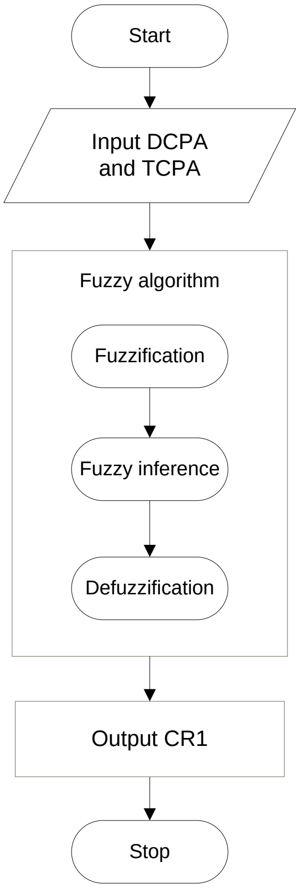

Figure 3.6: Flowchart of CR_1 calculation among vessel

In table 3.1, we defined five linguistic values for the variables TCPA and DCPA. Furthermore, we also defined five linguistic values for the CR_1.

Table 3.1: Range value of DCPA, TCPA and CR_1

DCPA	Value	TCPA	Value	CR_1	Value
0-2m	Small	0-4s	Small	0-0.4	Low
1-3m	Medium Small	2-6s	Medium Small	0.2-0.6	Medium Low
2-4m	Medium	4-8s	Medium	0.4-0.8	Medium
3-5m	Medium Big	6-10s	Medium Big	0.6-1.0	Medium High
4-6m	Big	8-10s	Big	0.8-1.0	High

Table 3.2 shows the reasoning rules of degree of CR_1. The fuzzy reasoning rule tables, in case when DCPA is S, MS, M, MB and B can be expressed in the forms of tables. For example, when DCPA is S and TCPA is S, the CR_1 should be H.

Table 3.2: Reasoning rule of degree of CR_1

CR_1		DCPA				
		S	MS	M	MB	B
TCPA	S	H	H	MH	MH	MH
	MS	H	MH	M	M	M
	M	MH	M	M	ML	ML
	MB	MH	M	ML	ML	L
	B	MH	M	ML	L	L

In our case the reasoning can be expressed in linguistic rules of two-input-one-output system as figure 3.7. DCPA and TCPA are the process state variables, CR_1 is the control variable. Here, we generated 25 rules for CR_1 of our proposed system:

```
1. If (DCPA is S) and (TCPA is S) then (CR1 is H) (1)
2. If (DCPA is S) and (TCPA is MS) then (CR1 is H) (1)
3. If (DCPA is S) and (TCPA is M) then (CR1 is MH) (1)
4. If (DCPA is S) and (TCPA is MB) then (CR1 is MH) (1)
5. If (DCPA is S) and (TCPA is B) then (CR1 is MH) (1)
6. If (DCPA is MS) and (TCPA is S) then (CR1 is H) (1)
7. If (DCPA is MS) and (TCPA is MS) then (CR1 is MH) (1)
8. If (DCPA is MS) and (TCPA is M) then (CR1 is M) (1)
9. If (DCPA is MS) and (TCPA is MB) then (CR1 is M) (1)
10. If (DCPA is MS) and (TCPA is B) then (CR1 is M) (1)
11. If (DCPA is MS) and (TCPA is S) then (CR1 is MH) (1)
12. If (DCPA is MS) and (TCPA is MS) then (CR1 is M) (1)
13. If (DCPA is MS) and (TCPA is M) then (CR1 is M) (1)
14. If (DCPA is MS) and (TCPA is MB) then (CR1 is ML) (1)
15. If (DCPA is MS) and (TCPA is B) then (CR1 is ML) (1)
16. If (DCPA is MB) and (TCPA is S) then (CR1 is MH) (1)
17. If (DCPA is MB) and (TCPA is MS) then (CR1 is M) (1)
18. If (DCPA is MB) and (TCPA is M) then (CR1 is ML) (1)
19. If (DCPA is MB) and (TCPA is MB) then (CR1 is ML) (1)
20. If (DCPA is MB) and (TCPA is B) then (CR1 is L) (1)
21. If (DCPA is B) and (TCPA is S) then (CR1 is MH) (1)
22. If (DCPA is B) and (TCPA is MS) then (CR1 is M) (1)
23. If (DCPA is B) and (TCPA is M) then (CR1 is ML) (1)
24. If (DCPA is B) and (TCPA is MB) then (CR1 is L) (1)
25. If (DCPA is B) and (TCPA is B) then (CR1 is L) (1)
```

Figure 3.7: All rules in case of CR_1

We designed the membership functions for DCPA, TCPA and CR_1 in our proposed CR_1 calculation module. Figure 3.8 and 3.9 are displaying the fuzzy membership functions graphically and figure 3.10 is displaying the fuzzy membership function of degree graphically. DCPA is defined by 5 linguistic variables using membership functions as shown in figure 3.8, which are defined between 0 and 6 based on the simulation condition. In this figure the x-axis is the DCPA input variable and y-axis shows the membership function value.

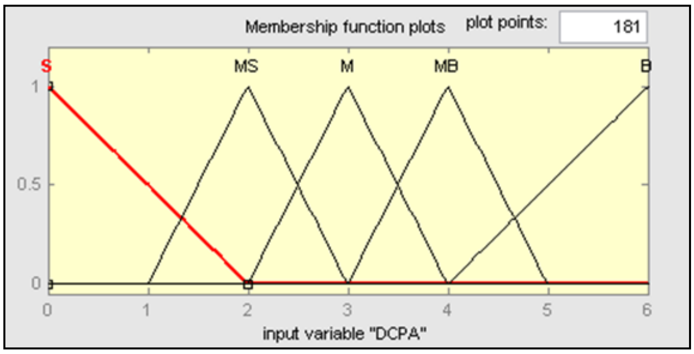

Figure 3.8: Membership function of DCPA

TCPA is also defined by 5 linguistic variables using membership functions as shown in figure 3.9, which are different defined between 0 and 10. In this figure the x-axis is the TCPA input variable and y-axis shows the membership function value.

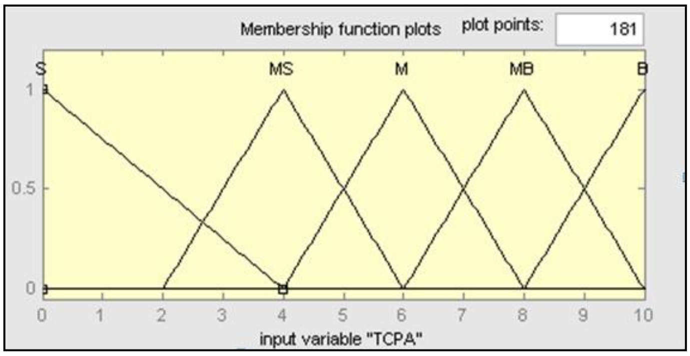

Figure 3.9: Membership function of TCPA

Figure 3.10 shows the membership function of degree of CR_1. The reasoning fuzzy table to determine CR_1 is provided using DCPA and TCPA as shown in table 3.2. CR_1 is defined between 0 and 1. The absolute value is proportional to the collision risk.

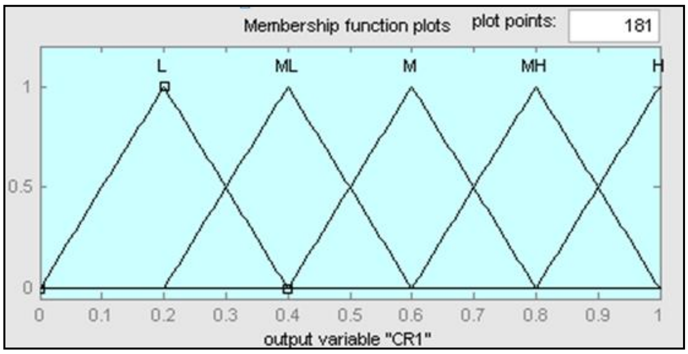

Figure 3.10: Membership function of degree of CR_1

3.2 Collision risk calculation method based on fuzzy comprehensive evaluation

This section will explain how to calculate CR_2 based on fuzzy comprehensive evaluation. The comprehensive evaluation result can be used as subjective evaluation, and also can be as objective one. Furthermore, system security is a progressively process. We can get perfect result through assessing the subordination of the factors. So we don't use the weighting of DCPA and TCPA to calculate collision risk, they applied fuzzy comprehensive evaluation in it. There are many factors effecting CR_2.

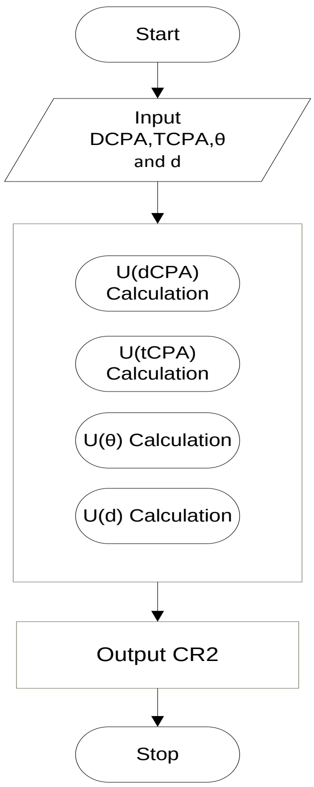

Figure 3.11: Flowchart of CR_2 Calculation among vessel

We only consider the major factors here, the distance between target ship and local ship d at current time, the position of target ship θ, DCPA and TCPA at current time. Figure 3.11 shows the flowchart of CR_2 Calculation.

So the target factors' discourse domain is:

$$u = \{d, \theta, t_{CPA}, d_{CPA}\} \tag{16}$$

The allocation of target factors weight is: $A = w_d, w_\theta, w_{dCPA}, w_{tCPA}$,

$$w_d > 0, w_\theta > 0, w_{dCPA} > 0, w_{tCPA} > 0, \text{and} w_d + w_\theta + w_{dCPA} + w_{tCPA} = 1,$$

Expert recommend: $w_d = 0.12, w_\theta = 0.12, w_{dCPA} = 0.38, w_{tCPA} = 0.38$

Target evaluation matrix is:

$$B = \begin{bmatrix} r_d \\ r_\theta \\ r_{dCPA} \\ r_{\text{tCPA}} \end{bmatrix} \tag{17}$$

$r_d, r_\theta, r_{dCPA}, r_{tCPA}$ are target risk membership.

$$0 \le r_d \le 1; 0 \le r_\theta \le 1; 0 \le r_{dCPA} \le 1; 0 \le r_{tCPA} \le 1;$$

Distance between two ships risk membership function at current time is:

$$u(d) = \begin{cases} 1 & d \le d_l \\ [(d_m - d)/(d_m - d_l)]^2 & d_l < d \le d_m \\ 0 & d > d_m \end{cases} \tag{18}$$

$$R = 1.7\cos(\theta - 19^\circ) + \sqrt{4.4 + 2.89\cos^2(\theta - 19^\circ)}, \quad (0^\circ \le \theta < 360^\circ) \tag{19}$$

$d_l = K_1 \cdot K_2 \cdot K_3 \cdot DLA, d_m = K_1 \cdot K_2 \cdot K_3 \cdot R$, d_l is distance of the last minute avoidance and d_m is distance of the adopt avoidance action at current time. K_1 decided by visibility, K_2 decided by water area status, K_3 decided by human factor, DLA is distance of the last minute action and R is the radius of arena at current time..

Position of target ship membership function at current time is:

$$u(\theta) = \begin{cases} \dfrac{1}{1 + (\theta / \theta_0)^2}, & 0 \le \theta < 180^\circ \\ \dfrac{1}{(\dfrac{360^\circ - \theta}{\theta_0})^2}, & 180^\circ \le \theta < 360^\circ \end{cases} \tag{20}$$

θ_0 is according to the velocity ratio K of local ship and target ship.

$$K = \frac{v_0}{v_t} \tag{21}$$

$$\theta_0 = \begin{cases} 40^\circ & K < 1 \\ 90^\circ & K = 1 \\ 180^\circ & K > 1 \end{cases} \tag{22}$$

DCPA risk membership function at current time is:

$$u(dCPA) = \begin{cases} 1 & dCPA \le \lambda \\ \frac{1}{2} - \frac{1}{2}\sin[\frac{\pi}{dCPA_0 - \lambda}(dCPA - \frac{dCPA_0 + \lambda}{2})], & \lambda < dCPA \le dCPA_0 \\ 0 & dCPA > dCPA_0 \end{cases} \tag{23}$$

$dCPA_0 = 1nmile$, $\lambda = 2(L_o + L_t)$, L_o, L_t are the length of local and target ship.

TCPA risk membership function at current time is:

$$u(tCPA) = \begin{cases} 1 & tCPA \le t_1 \\ \frac{t_2 - tCPA}{t_2 - t_1}, & t_1 < tCPA \le t_2 \\ 0 & tCPA > t_2 \end{cases} \tag{24}$$

$$t_1 = \frac{\sqrt{(d_l{}^2 - \lambda^2)}}{v_s} \tag{25}$$

$$t_2 = \frac{\sqrt{(d_m{}^2 - dCPA_0{}^2)}}{v_s} \tag{26}$$

According to the fuzzy comprehensive evaluation method:

$$CR_2 = A \cdot B = (w_d, w_\theta, w_{dCPA}, w_{tCPA}) \cdot \begin{bmatrix} r_d \\ r_\theta \\ r_{dCPA} \\ r_{tCPA} \end{bmatrix} \tag{27}$$

CR_2 at current time is:

$$CR_2 = [w_d u_d + w_\theta u_\theta + w_{dCPA} u_{dCPA} + w_{tCPA} u_{tCPA}] \tag{28}$$

3.3 Hybrid collision risk calculation method

In section 3.1 and section 3.2 we have explained how to compute CR_1 and CR_2. In this section based on these computations we introduce our hybrid collision risk calculation technique. The technique utilizes both CR_1 and CR_2 in order to obtain the better results. The algorithm is based on steps depicted in figure 3.12.

Once we compute the values for CR_1 and CR_2 we need to know which collision risk is better in order to obtain that we have introduce a fuzzy function to compute the HCR by combining CR_1 and CR_2, table 3.8 depicts the rules for the fuzzy function.

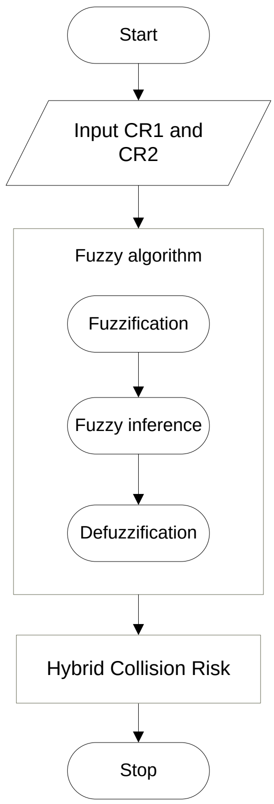

Figure 3.12: Flowchart of HCR calculation among vessel

Now we designed five linguistic values for the variables HCR as shown in table 3.3. Figure 3.12 shows the flowchart of HCR calculation of each ship using fuzzy logic. Here, we will input the CR_1 and CR_2 and HCR will be output after apply fuzzy logic again.

Table 3.3: Range value of CR_1, CR_2 and hybrid collision risk

CR_1	**Value**	**CR_2**	**Value**	**HCR**	**Value**
0-0.4	Low	0-0.4	Low	0-0.4	Low
0.2-0.6	Medium Low	0.2-0.6	Medium Low	0.2-0.6	Medium Low
0.4-0.8	Medium	0.4-0.8	Medium	0.4-0.8	Medium
0.6-1.0	Medium High	0.6-1.0	Medium High	0.6-1.0	Medium High
0.8-1.0	High	0.8-1.0	High	0.8-1.0	High

Table 3.4 shows the reasoning rules of degree of HCR. The fuzzy reasoning rule tables, in case when CR_1 is L, ML, M, MH and H can be expressed in the forms of table.

Table 3.4: Reasoning rule of degree of hybrid collision risk

HCR		CR_1				
		L	ML	M	MH	H
CR_2	L	L	L	ML	M	MH
	ML	L	ML	ML	M	MH
	M	ML	ML	M	M	MH
	MH	M	M	M	HL	H
	H	MH	MH	HH	H	H

In this case the reasoning can be expressed in linguistic rules of two-input-one-output system as figure 3.13. CR_1 and CR_2 are the process state variables, HCR is the control variable.

```
1. If (CR1 is L) and (CR2 is L) then (HCR is L) (1)
2. If (CR1 is L) and (CR2 is ML) then (HCR is ML) (1)
3. If (CR1 is L) and (CR2 is M) then (HCR is ML) (1)
4. If (CR1 is L) and (CR2 is MH) then (HCR is M) (1)
5. If (CR1 is L) and (CR2 is H) then (HCR is MH) (1)
6. If (CR1 is ML) and (CR2 is L) then (HCR is L) (1)
7. If (CR1 is ML) and (CR2 is ML) then (HCR is ML) (1)
8. If (CR1 is ML) and (CR2 is M) then (HCR is ML) (1)
9. If (CR1 is ML) and (CR2 is MH) then (HCR is M) (1)
10. If (CR1 is ML) and (CR2 is H) then (HCR is MH) (1)
11. If (CR1 is M) and (CR2 is L) then (HCR is ML) (1)
12. If (CR1 is M) and (CR2 is ML) then (HCR is ML) (1)
13. If (CR1 is M) and (CR2 is M) then (HCR is M) (1)
14. If (CR1 is M) and (CR2 is MH) then (HCR is M) (1)
15. If (CR1 is M) and (CR2 is H) then (HCR is MH) (1)
16. If (CR1 is MH) and (CR2 is L) then (HCR is M) (1)
17. If (CR1 is MH) and (CR2 is ML) then (HCR is M) (1)
18. If (CR1 is MH) and (CR2 is M) then (HCR is M) (1)
19. If (CR1 is MH) and (CR2 is MH) then (HCR is H) (1)
20. If (CR1 is MH) and (CR2 is H) then (HCR is H) (1)
21. If (CR1 is H) and (CR2 is L) then (HCR is MH) (1)
22. If (CR1 is H) and (CR2 is ML) then (HCR is MH) (1)
23. If (CR1 is H) and (CR2 is M) then (HCR is MH) (1)
24. If (CR1 is H) and (CR2 is MH) then (HCR is H) (1)
25. If (CR1 is H) and (CR2 is H) then (HCR is H) (1)
```

Figure 3.13: All rules in case of hybrid collision risk

In the case of hybrid collision risk calculation at current time, we designed the membership functions for CR_1, CR_2 and hybrid collision risk at current time in our proposed system. Figures 3.14 and 3.15 are displaying the fuzzy membership functions graphically of CR_1 and CR_2. Figure 3.16 is displaying the fuzzy membership function of degree of hybrid collision risk graphically.

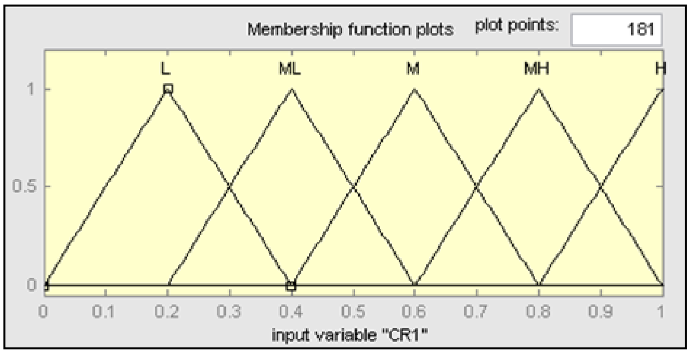

Figure 3.14: Membership function of CR_1

Figure 3.14 shows the membership function of CR_1. CR_1 is defined by 5 linguistic variables using membership functions, which are defined between 0 and 1as shown in section 3.1.3. In this figure the x-axis is the CR_1 input variable.

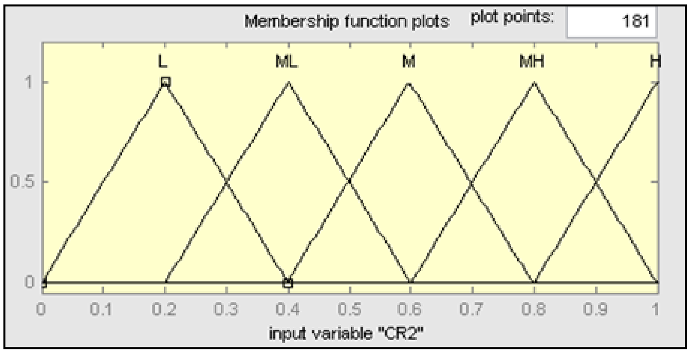

Figure 3.15: Membership function of CR_2

Figure 3.15 shows the membership function of CR_2. CR_2 is also defined by 5 linguistic variables using membership functions, which are defined between 0 and 1. In this figure the x-axis is the CR_2 input variable.

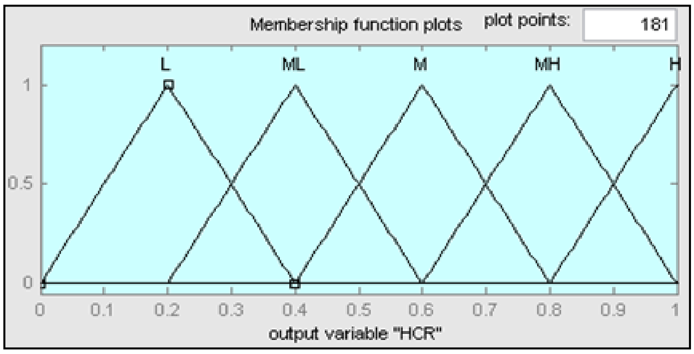

Figure 3.16: Membership function degree of hybrid Collision Risk

Figure 3.16 shows the membership function of degree of HCR. The reasoning fuzzy table to determine HCR is provided using CR_1 and CR_2 as shown in table 3.4. HCR is defined between 0 and 1. In this figure the x-axis is the HCR output variable.

3.4 Simulation and performance analysis

3.4.1 Simulation environment

To validate the proposed system, we developed a real-time simulator which can get the input from Radar directly. We programmed the simulator by using C# and our experimental environment as shown in table 3.5.

Table 3.5: Simulation environment

Module	Hardware	Software	remark
Vessel information collection module	Intel(R) Xeon(R) CPU W3503 @2.4GHz 2.39GHz 4GB RAM	Microsoft Visual Studio	C# Windows 7
DCPA and TCPA calculation module	Intel(R) Xeon(R) CPU W3503 @2.4GHz 2.39GHz 4GB RAM	Microsoft Visual Studio	C# Windows 7
Collision risk calculation module	Intel(R) Xeon(R) CPU W3503 @2.4GHz 2.39GHz 4GB RAM	Microsoft Visual Studio	C# Windows 7
Vessel location prediction module	Intel(R) Xeon(R) CPU W3503 @2.4GHz 2.39GHz 4GB RAM	Mat lab R2010a and Microsoft Visual Studio	Windows 7
Avoidance control module	Intel(R) Xeon(R) CPU W3503 @2.4GHz 2.39GHz 4GB RAM	Microsoft Visual Studio	C# Windows 7

3.4.2 Implementation results of simulator

In the real navigation situation, there mainly divided into three situations: head-on, overtaken and crossing. So we designed three scenarios to test the performance of the system. We perform performance evaluation of the proposed algorithm – hybrid collision risk – with fuzzy collision risk and evaluation collision risk for three different scenarios depicted in figures 3.25, 3.27 and 3.29.

Figure 3.17 shows the display of simulator. The display of simulator is divided into map screen, Initial information of vessels Input center, Vessel control Center, Prediction of vessels visual window, collision risk visual window, real-time Information window and Best deflection control window.

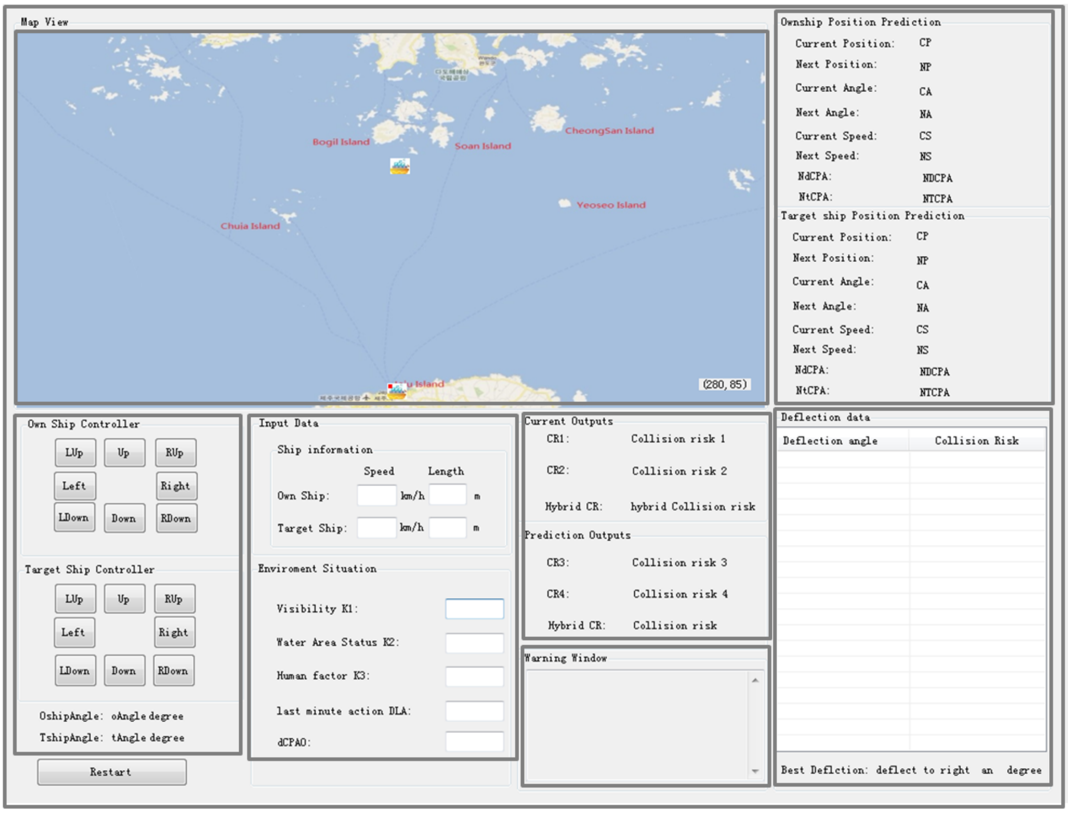

Figure 3.17: Display of simulator

We will explain the display of simulator screen in detailed as shown in figure 3.18 to figure

3.24. Figure 3.18 shows the Map screen that upload the map for vessel to navigate. And we will set the initial position of own and target ship on the map.

Figure 3.18: Display of Map screen

Figure 3.19 shows the Initial information of vessels Input center that set the information of own and target vessel, like the length of each ship and give each ship's speed. We also set the environment situation of vessel navigation in this center.

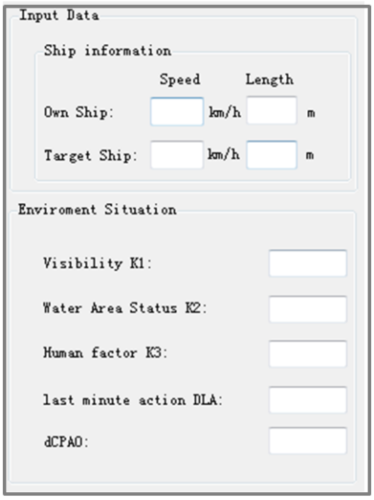

Figure 3.19: Display of Initial information input center

Figure 3.20 shows the Vessel control center that made of eight buttons to indicate eight direction including Up, Down, Left, Right, Left-Up, Left-down, Right-Up and Right-down.

There is 45 degree difference between each direction.

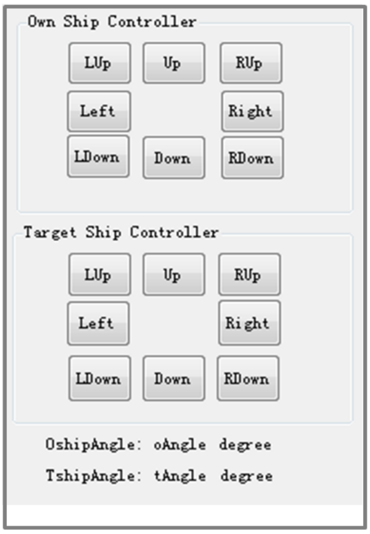

Figure 3.20: Display of vessel control center

Figure 3.21 shows the prediction of vessels visual window that displaying the own and target vessel prediction information including position, navigation angle and speed of vessels. The DCPA and TCPA of prediction data between vessels also are shown in this figure.

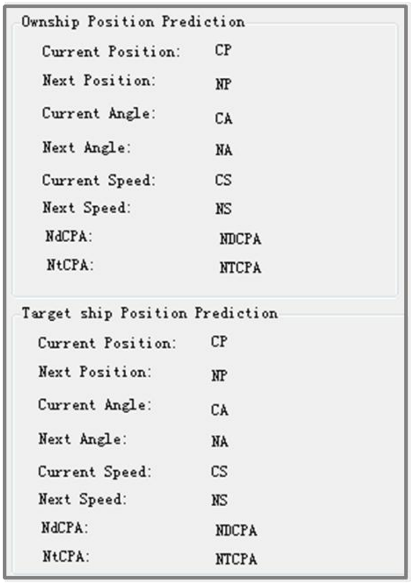

Figure 3.21: Display of prediction of vessel visual window

Figure 3.22 shows the collision risk visual window shows the results of hybrid collision risk and prediction of collision risk. We also output the CR_1, CR_2, prediction CR_1 and prediction CR_2 for comparison difference. Figure 3.23 shows the real-time information visual window that will send the state information of vessels in real-time to mariner. It is convenient to mariner to make the right decision based on the state information of navigation.

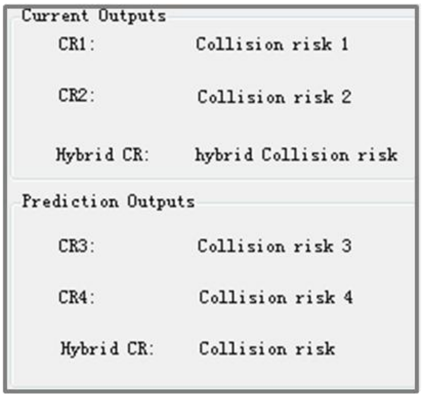

Figure 3.22: Display of collision risk visual window

Figure 3.23: Display of real-time information visual window

Figure 3.24 is the diagram of best deflection control window. When the hybrid collision risk is bigger than threshold, the ship will output all the collision risk after deflect the ship from 0 to 360 degree and based on this mariner is convenient to make the best decision to change the course of ship.

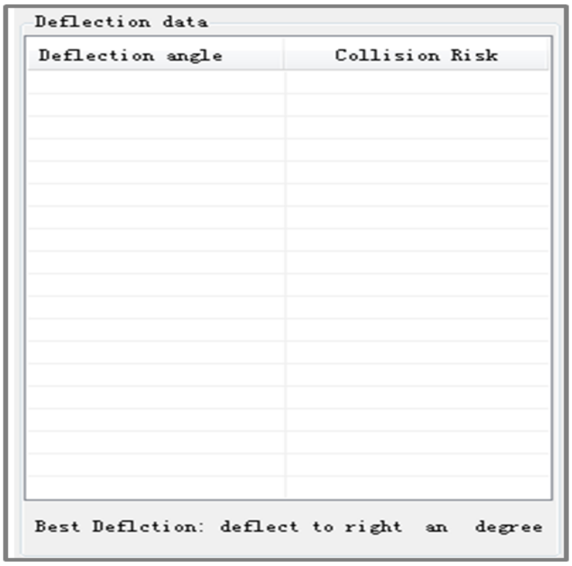

Figure 3.24: Display of Best deflection control window

3.4.3 Simulation results and performance analysis

Figure 3.26, 3.28 and 3.30 explains performance comparison between proposed hybrid collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation for three scenarios presented in figure 3.25, 3.27 and 3.29 respectively. We recorded the results of each scenario by using our proposed system and displaying the comparative results in figure 3.26, 3.28 and 3.30. In the old schemes, they just calculated the collision risk by using two vessels we also calculated the hybrid collision risk for better comparison.

3.4.2.1 Head-on scenario

In the first scenario, we set own vessel and target vessel are moving with same speed 3m/s as shown in figure 3.25. We set 90° for own vessel and 270° for target vessel while the starting points of both vessels are different. We performed the simulation and recorded the results.

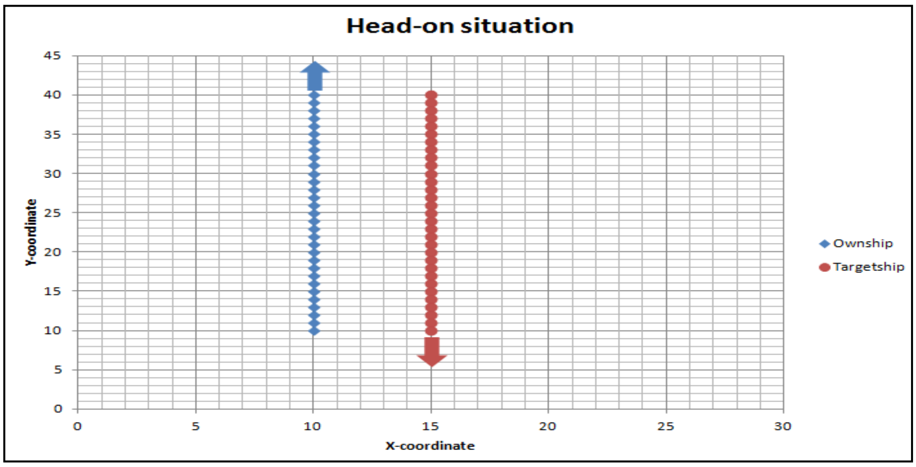

Figure 3.25: Navigation of head-on scenario

It show the variation of hybrid collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation in figure 3.26. Figure 3.25 shows the scenario. In this scenario two ships are passing nearby each other with a certain distance. When the ships start moving towards each other, this distance was long and the DCPA and TCPA was also high, which mean the collision risk is low. As the two ships approaches each other the distance between two ships is decreasing and also the collision risk is linearly increasing as shown in figure 3.26. When the two ships reach each other and the distance between them is constant (remain same). The collision risk is uniform. However when the two ships crossed each other and the distance between them is increasing. The collision risk is linearly decreasing. The results show that hybrid collision risk performance better than other techniques. It is because of the reason that hybrid collision risk computes risk value more efficiently than individual risk computation. Furthermore, hybrid collision risk computes calculate risk by using next predicted position that helps and timely avoidance of the calculated risk. Our experiments showed that comparison of CR_1 and CR_2 had significant impact on the output of the risk computation.

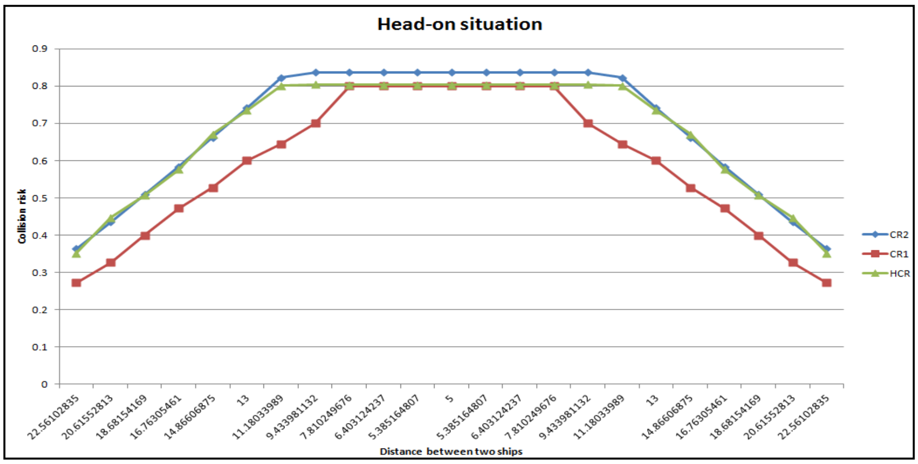

Figure 3.26: Simulation result of head-on scenario

3.4.2.2 Overtaken scenario

In the second scenario, we have examined our hybrid algorithm when two ships have different speed. Figure 3.27 shows the route of own ship and target ship scenario. We set own vessel and target vessel are moving with the speed of 3m/s and 4m/s respectively. And we changed the courses of own and target vessels from previous degree to same 90° and performed the simulation. The simulation results can be seen in figure 3.28.

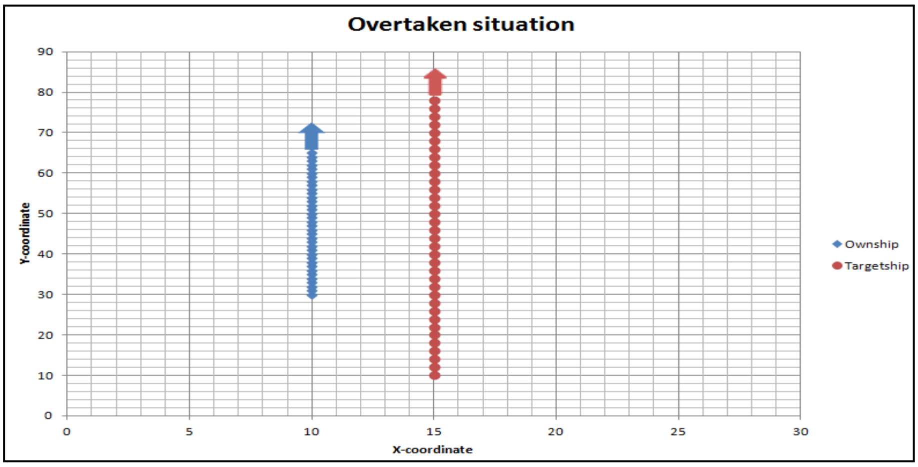

Figure 3.27: Navigation of overtaken scenario

In figure 3.28 it shown the variation of hybrid collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation. In figure 3.27 we can see when the target ship overtaking own ship from long distance to approach each other, the collision risk will increased linearly and when the target ship approaching own ship the collision risk will be uniform for a certain period of time. However, when the own ship overtaken by target ship the collision risk will decreased linearly. The results show that hybrid collision risk performance better than other techniques.

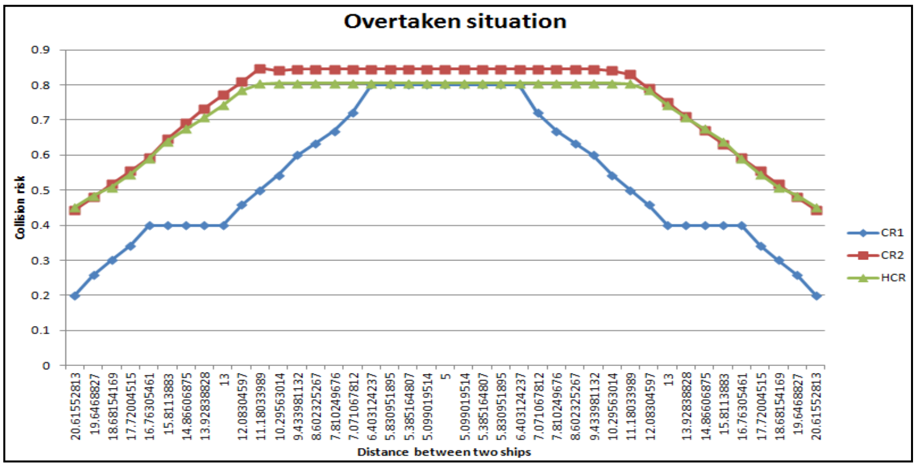

Figure 3.28: Simulation results of overtaken scenario

3.4.2.3 Crossing scenario

In the third scenario, we turn the angles again and at this time we set 45° course for own vessel and 100° course for target ship. Figure 3.29 depicts the presented scenario. It has been shown that ships are colliding near the center of their journey. We performed the simulation and recorded the results for this scenario.

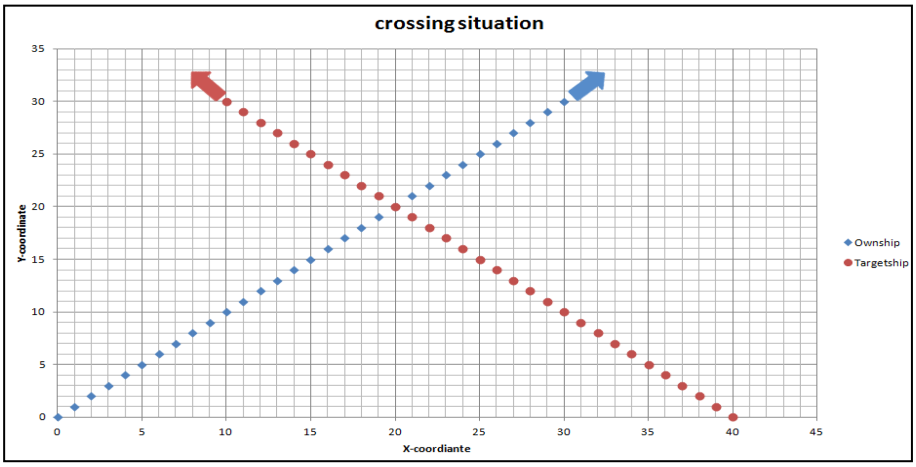

Figure 3.29: Diagram of navigation of crossing scenario

In figure 3.30 it show the variation of hybrid collision risk, collision risk based on fuzzy and collision risk based on fuzzy comprehensive evaluation. In figure 3.29, when the target and own ship from long distance to crossing each other, the collision risk will increased linearly and when two ships approached the collision risk will be uniform for a certain period of time and when the two ships passed each other the collision risk will decreased linearly. The results show that hybrid collision risk performance better than other techniques. In figure we can see hybrid collision risk increases linearly but CR_1 and CR_2 increase non-linearly. This shows the fact of fuzzy function only output.

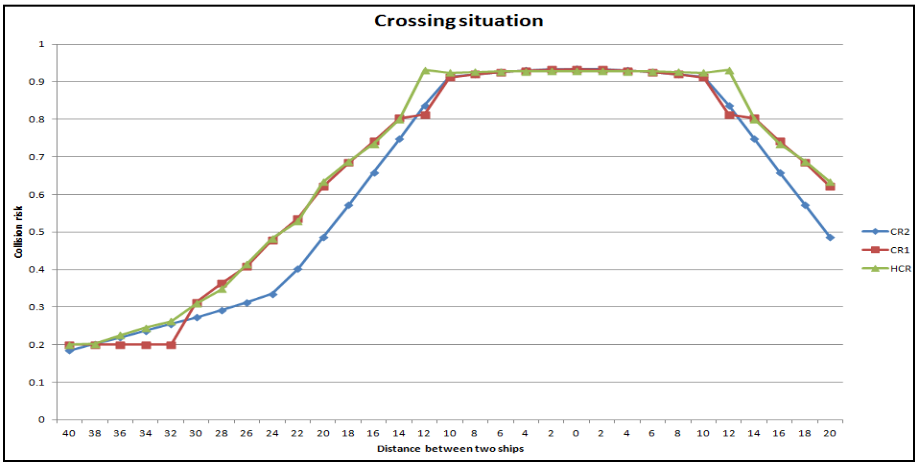

Figure 3.30: Diagram of simulation results of crossing scenario

4. Hybrid collision risk calculation method based on prediction

In this chapter we present the collision risk prediction module of proposed system that is shown in figure 4.1. This module will predict the hybrid collision risk at next time stamp. Firstly we will predict the location of vessels of next time. Secondly, we present a mechanism to calculate the prediction $DCPA^P$ and $TCPA^P$ between own and target ship using the location prediction information of ships. Thirdly, the CR_3 will be calculating based on fuzzy after input the prediction $DCPA^P$ and $TCPA^P$. Meanwhile, the CR_4 be calculating based on the membership functions of prediction $DCPA^P$, $TCPA^P$, d^P (prediction distance between ships of next time) and prediction navigation angle of target ship. At last, the CR_3 and CR_4 will be input to fuzzy logic system again and we will get the prediction hybrid collision risk at next time.

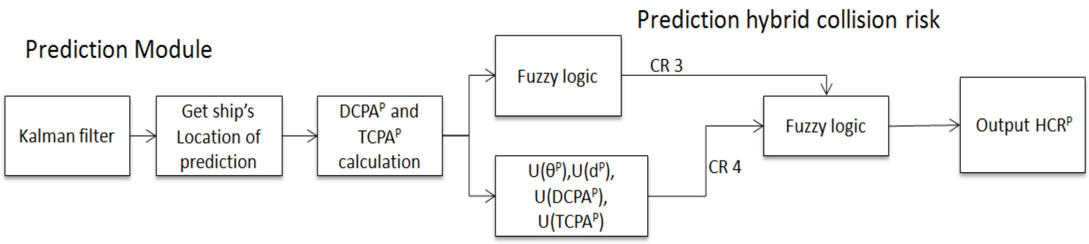

Figure 4.1: Hybrid collision risk prediction module of proposed system

Figure 4.2 shows the flowchart of hybrid collision risk prediction at next time. We define the next time is t+x. Firstly, we predict the location information of each ship at next time by using the Kalman filter. The $DCPA^P$ and $TCPA^P$ calculated based on predicting ship's location and navigation angle. After that input the $DCPA^P$ and $TCPA^P$ to fuzzy logic system calculate the CR_3 and CR_4 calculated based on membership functions of navigation angle θ^P, distance between two ships d^P, $DCPA^P$ and $TCPA^P$. At last, the prediction hybrid collision risk calculated by using fuzzy logic.

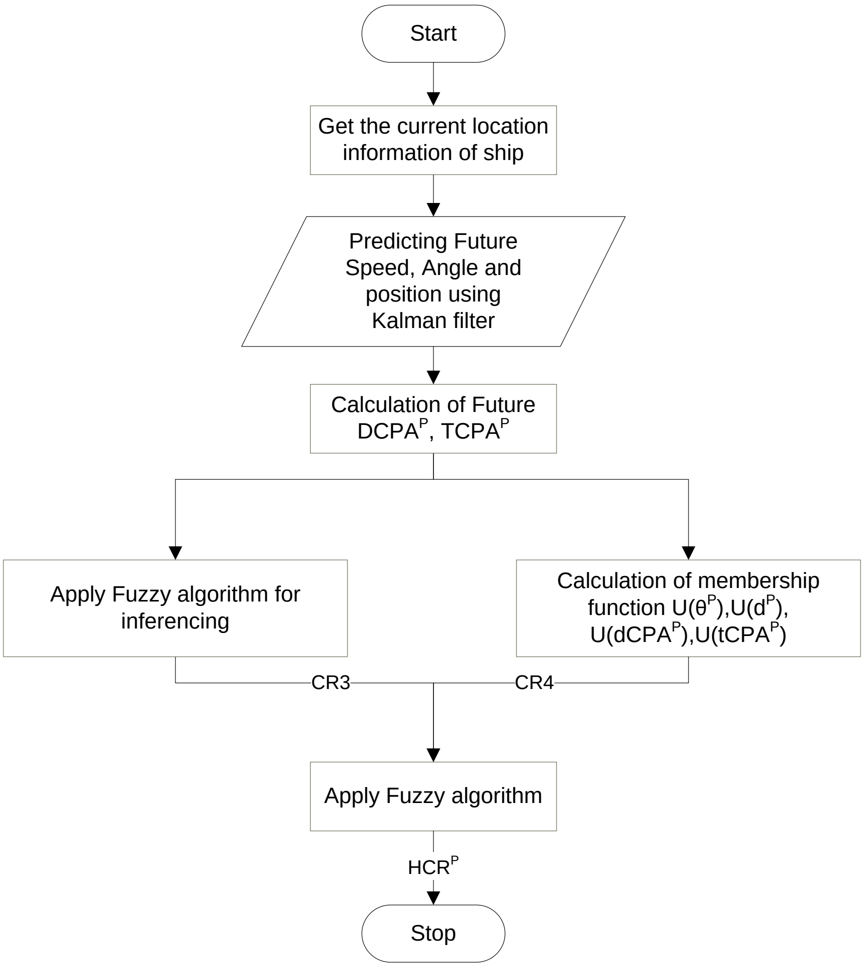

Figure 4.2: Flowchart of hybrid collision risk prediction

4.1 Kalman Filter for ship position estimation

The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error. The filter is very powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modeled system is unknown. In a Dynamic Positioning application a Kalman filter is used to estimate the state of the vessel (for which a dynamics model has been developed) based on noisy measurements from reference systems and sensors.

In 1960, R.E. Kalman published his famous paper describing a recursive solution to the discrete data linear filtering problem. Since that time, due in large part to advances in digital computing; the Kalman filter has been the subject of extensive research and application, particularly in the area of autonomous or assisted navigation. A very “friendly” introduction to the general idea of the Kalman filter can be found in Chapter 1 of (Maybeck79), while a more complete introductory discussion can be found in (Sorenson70), which also contains some interesting historical narrative. More extensive references include (Gelb74; Grewal93; Maybeck79; Lewis86; Brown92; Jacobs93).

We use the Kalman Filter to estimate the ship position, angle and speed at time t+x, where x is a threshold time that is used for estimation. The two equations of Kalman Filter are as follows:

$$x_{\mathrm{k}} = \mathrm{A}x_{k-1} + bu_k + w_{k-1} \tag{29}$$

$$z_{\mathrm{k}} = \mathrm{H}x_k + v_k \tag{30}$$

In equation (29), each x_k may be evaluated by using a linear stochastic equation (the first one). Any x_k is a linear combination of its previous value plus a control signal u_k and a process noise (which may be hard to conceptualize). Remember that, most of the time, there is no control signal u_k. The equation (30) tells that any measurement value (which we are not sure its accuracy) is a linear combination of the signal value and the measurement noise. Both noised are considered as Gaussian noise.

After we gathered all the information we need and started the process, now we can iterate through the estimates. Keep in mind that the previous estimates will be the input for the current state.

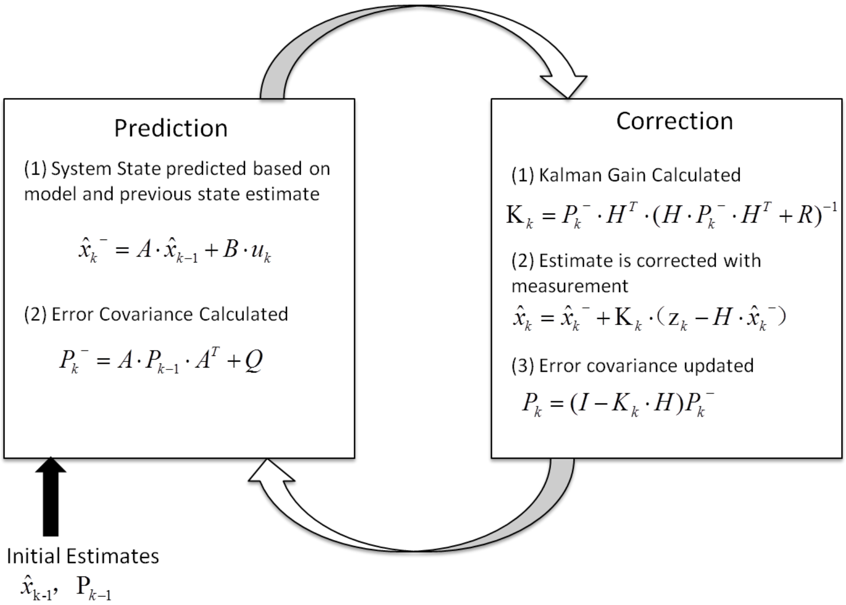

Figure 4.3: Predictor and Corrector Structure of Kalman Filter with Equations

Here, $\hat{x}_k$ is the "prior estimate" which in a way means the rough estimate before the measurement update correction. Moreover, P_k^- is the "prior error covariance". We use these "prior" values in our Measurement Update equations.

In Measurement Update equations, we find $\hat{x}_k$, which is the estimation of x at time k. In addition, we find P_k which is necessary for the k (future) estimate, together with $\hat{x}_k$. The Kalman Gain (K_k) we evaluate is not needed for the next iteration step; it is a hidden, mysterious and the most important part of this set of equations.

The values we evaluate at Measurement Update stage are also called "posterior" values. After applying the Kalman filter and finding the ship's position, speed, and angle at time t+x, we apply the risk calculation mechanism to find the hybrid collision risk at time t+x.

In our proposed system we just need the position state of own and target ship that consists of vessel position x and position y, so we designed the $x_k = \begin{Bmatrix} (Position)x_k \\ (Position)y_k \end{Bmatrix}$. We apply Kalman Filter to estimate the next time position based on current position. Figure 4.4 shows the prediction algorithm of Kalman filter. In this figure it has one input and one output, input the measurement z_t it will process internal and output the estimate value $\hat{x}_{t+x}$. The internal calculation divides into four steps. The first step predicts the state of the vessel and error covariance. The second step calculates the Kalman Gain. The third step corrects the estimate value and the last step calculates the error covariance.

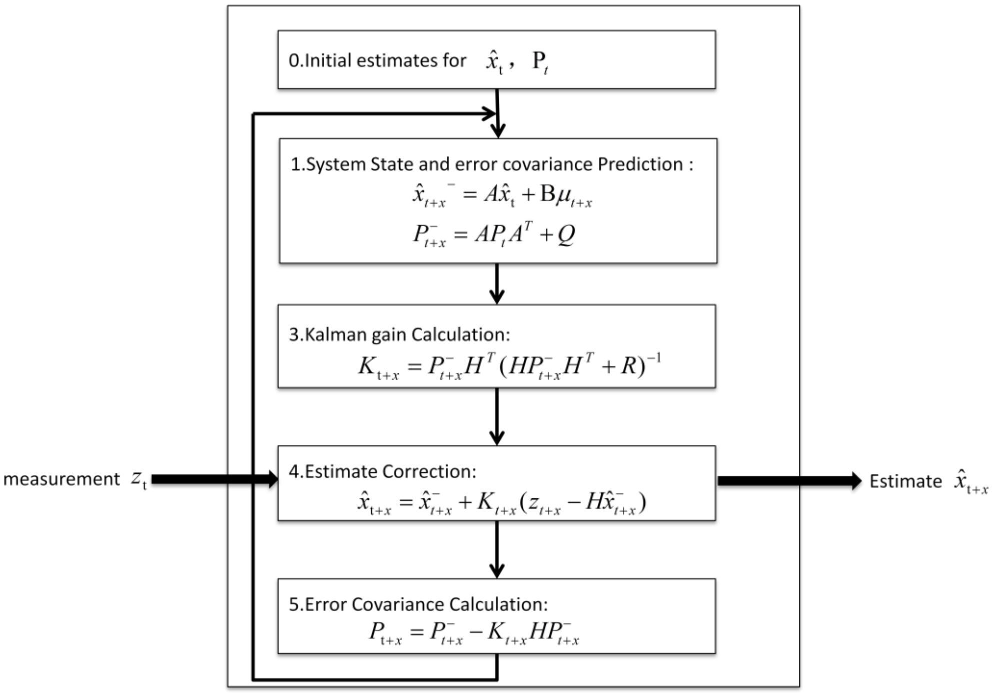

Figure 4.4: Algorithm of Kalman Filter

4.2 Prediction of DCPA^P and TCPA^P

We predict the location of vessels at next time using Kalman filter. At next time the vessel O (x_O^P, y_O^P) and Vessel T (x_T^P, y_T^P) are moving with speed (V_O^P, V_T^P). In the figure 3.4, the prediction DCPA^P and TCPA^P at next time between vessels O and T can be calculated by using the equation (35) and (36).

We defined prediction relative speed to target ship measured from own ship is V_r^P and is calculated as:

$$V_r^P = \sqrt{V_O^{P\,2} + V_T^{P\,2} - 2|V_O^P V_T^P|\cos(\theta_T^P - \theta_O^P)} \tag{31}$$

We defined the slope intercept form of line *TP* is $Y - y_T^P = k(X - x_T^P)$ which parallel with relative speed and start from target ship's position.

$$k^P = \tan\theta_r^P \tag{32}$$

$$\theta_r^P = \theta_T^P + \theta \tag{33}$$

$$\theta = \arccos\left(\frac{V_r^{P\,2} + V_T^{P\,2} - V_O^{P\,2}}{2V_r^P V_T^P}\right) \tag{34}$$

Mathematically, at next time, the prediction $DCPA^P$ between vessels *O* and *T* from VTS can be calculated by using the following equations.

$$DCPA^P = |OP| = \frac{|y_T^P - x_T^P \tan\theta_r^P)|}{\sqrt{\tan^2\theta_r^P + 1}} \tag{35}$$

Mathematically, at next time, the prediction $TCPA^P$ between vessels *O* and *T* from VTS can be calculated by using the following equations.

$$TCPA^P = \frac{|TP|}{V_r^P} = \frac{\sqrt{(x_T^{P\,2} + y_T^{P\,2}) - DCPA^{P\,2}}}{V_r^P} \tag{36}$$

4.3 Collision risk calculation method based on prediction using fuzzy

We predict the prediction $DCPA^P$ and $TCPA^P$ based on predict the location of vessel at next time in section 4.2. In this section we compute the CR_3 using the values of prediction $DCPA^P$ and $TCPA^P$. Figure 4.5 shows the flowchart of CR_3 prediction at next time. Then, using prediction $DCPA^P$ and $TCPA^P$ as the input and applying fuzzy logic algorithm we output the prediction of degree of CR_3 at next time.

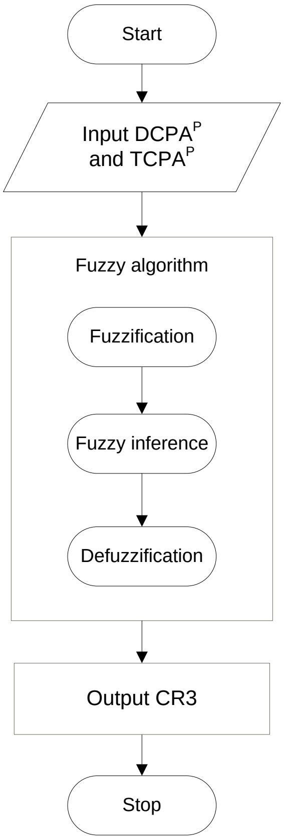

Figure 4.5: Flowchart of CR_3 calculation among vessel

There are five linguistic values for the variables prediction $DCPA^P$ and $TCPA^P$ at next time as be shown in table 4.1.

Table 4.1: Range value of prediction $DCPA^P$, $TCPA^P$ and CR_3

$DCPA^P$	Value	$TCPA^P$	Value	CR_3	Value
0-2m	Small	0-4s	Small	0-0.4	Low
1-3m	Medium Small	2-6s	Medium Small	0.2-0.6	Medium Low
2-4m	Medium	4-8s	Medium	0.4-0.8	Medium
3-5m	Medium Big	6-10s	Medium Big	0.6-1.0	Medium High
4-6m	Big	8-10s	Big	0.8-1.0	High

The fuzzy reasoning rule tables, in case when prediction $DCPA^P$ of next time is S, MS, M, MB and B can be expressed in the forms of tables 4.2.

Table 4.2: Reasoning rule of degree of CR_3

CR_3		DCPA^P				
		S	MS	M	MB	B
TCPA^P	S	H	H	MH	MH	MH
	MS	H	MH	M	M	M
	M	MH	M	M	ML	ML
	MB	MH	M	ML	ML	L
	B	MH	M	ML	L	L

In this case the reasoning can be expressed in linguistic rules of two-input-one-output system as figure 4.6. DCPA^P and TCPA^P are the process state variables, CR_3 is the control variable. Here, we generated 25 rules for CR_3 of our proposed system:

1. If (DCPA" is S) and (TCPA" is S) then (CR3 is H) (1)
2. If (DCPA" is S) and (TCPA" is MS) then (CR3 is H) (1)
3. If (DCPA" is S) and (TCPA" is M) then (CR3 is MH) (1)
4. If (DCPA" is S) and (TCPA" is MB) then (CR3 is MH) (1)
5. If (DCPA" is S) and (TCPA" is B) then (CR3 is MH) (1)
6. If (DCPA" is MS) and (TCPA" is S) then (CR3 is H) (1)
7. If (DCPA" is MS) and (TCPA" is MS) then (CR3 is MH) (1)
8. If (DCPA" is MS) and (TCPA" is M) then (CR3 is M) (1)
9. If (DCPA" is MS) and (TCPA" is MB) then (CR3 is M) (1)
10. If (DCPA" is MS) and (TCPA" is B) then (CR3 is M) (1)
11. If (DCPA" is M) and (TCPA" is S) then (CR3 is MH) (1)
12. If (DCPA" is M) and (TCPA" is MS) then (CR3 is M) (1)
13. If (DCPA" is M) and (TCPA" is M) then (CR3 is M) (1)
14. If (DCPA" is M) and (TCPA" is MB) then (CR3 is ML) (1)
15. If (DCPA" is M) and (TCPA" is B) then (CR3 is ML) (1)
16. If (DCPA" is MB) and (TCPA" is S) then (CR3 is MH) (1)
17. If (DCPA" is MB) and (TCPA" is MS) then (CR3 is M) (1)
18. If (DCPA" is MB) and (TCPA" is M) then (CR3 is ML) (1)
19. If (DCPA" is MB) and (TCPA" is MB) then (CR3 is ML) (1)
20. If (DCPA" is MB) and (TCPA" is B) then (CR3 is L) (1)
21. If (DCPA" is B) and (TCPA" is S) then (CR3 is MH) (1)
22. If (DCPA" is B) and (TCPA" is MS) then (CR3 is M) (1)
23. If (DCPA" is B) and (TCPA" is M) then (CR3 is ML) (1)
24. If (DCPA" is B) and (TCPA" is MB) then (CR3 is L) (1)
25. If (DCPA" is B) and (TCPA" is B) then (CR3 is L) (1)

Figure 4.6: All rules in case of CR_3

We designed the membership functions for prediction DCPA^P, TCPA^P and CR_3 at next time in our proposed solution. Figures 4.7 and 4.8 are displaying the fuzzy membership functions graphically and figure 4.9 is displaying the fuzzy membership function of degree graphically. Figure 4.7 shows the membership function of prediction DCPA^P. DCPA^P is defined by 5 linguistic variables same as DCPA, which are also defined between 0 and 6. In this figure the x-axis is the DCPA^P input variable.

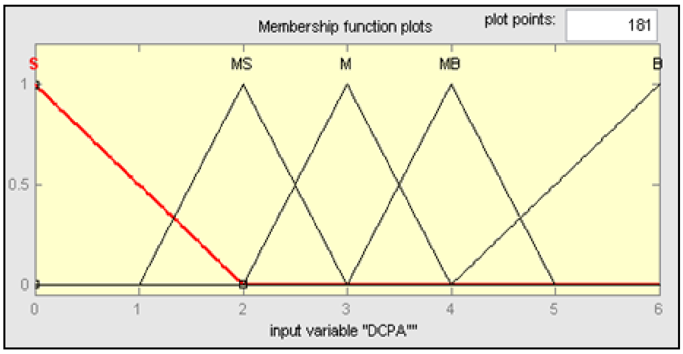

Figure 4.7: Membership function of prediction $DCPA^P$

$TCPA^P$ is also defined by 5 linguistic variables using membership functions as shown in figure 4.8, which are defined between 0 and 10 same as TCPA. In this figure the x-axis is the $TCPA^P$ input variable.

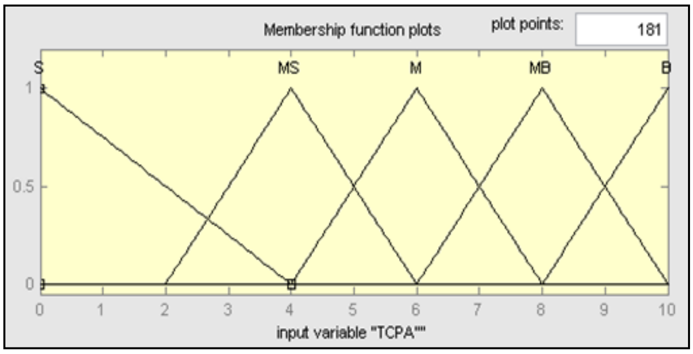

Figure 4.8: Membership function of prediction $TCPA^P$

Figure 4.9 shows the membership function of degree of CR_3. The reasoning fuzzy table to determine CR_3 is provided using $DCPA^P$ and $TCPA^P$ as shown in table 4.2. CR_3 is defined between 0 and 1. In this figure the x-axis is the CR_3 output variable.

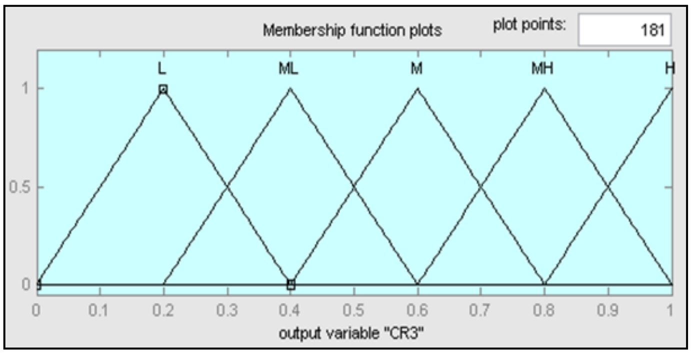

Figure 4.9: Membership function of degree of CR_3

4.4 Collision risk calculation method based on prediction using fuzzy comprehensive evaluation

This section will explain how to calculate CR_4 based on fuzzy comprehensive evaluation. Figure 4.10 shows the flowchart of CR_4 Calculation. Here we also only consider the major factors here, the prediction distance between target ship and local ship d^P, the prediction position of target ship θ^P prediction $DCPA^P$ and $TCPA^P$ at next time. The CR_4 will be calculated by using following equations.

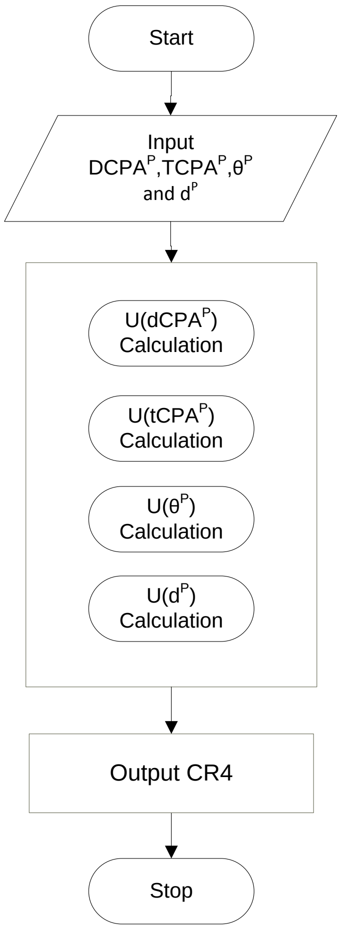

Figure 4.10: Flowchart of CR_4 calculation among vessel

So the prediction target factors' discourse domain is:

$$u^P = \{d^P, \theta^P, t_{CPA}{}^P, d_{CPA}{}^P\} \quad (37)$$

The allocation of prediction target factors weight is same with above.

Prediction target evaluation matrix is:

$$B^P = \begin{bmatrix} r_d^P \\ r_\theta^P \\ r_{dCPA}^P \\ r_{tCPA}^P \end{bmatrix} \tag{38}$$

$r_d^P, r_\theta^P, r_{dCPA}^P, r_{tCPA}^P$ are prediction target risk membership.

$$0 \le r_d^P \le 1;\ 0 \le r_\theta^P \le 1; 0 \le r_{dCPA}^P \le 1; 0 \le r_{tCPA}^P \le 1;$$

Prediction distance risk membership function is:

$$u(d^P) = \begin{cases} 1 & d^P \le d_l^P \\ [(d_m^P - d^P)/(d_m^P - d_l^P)]^2 & d_l^P < d^P \le d_m^P \\ 0 & d^P > d_m^P \end{cases} \tag{39}$$

$$R^P = 1.7\cos(\theta^P \text{ -}19^\circ) + \sqrt{4.4 + 2.89\cos^2(\theta^P \text{ -}19^\circ)}, \quad (0^\circ \le \theta^P < 360^\circ) \tag{40}$$

$$d_m^P = K_1 \cdot K_2 \cdot K_3 \cdot R^P \tag{41}$$

Prediction position of target ship membership function is:

$$u(\theta^P) = \begin{cases} \dfrac{1}{1 + (\theta^P / \theta_o^P)^2}, & 0 \le \theta^P < 180^\circ \\ \dfrac{1}{(\dfrac{360^\circ - \theta^P}{\theta_o^P})^2}, & 180^\circ \le \theta^P < 360^\circ \end{cases} \tag{42}$$

$$K^P = \frac{v_o^P}{v_t^P} \tag{43}$$

$$\theta_o^P = \begin{cases} 40^\circ & K^P < 1 \\ 90^\circ & K^P = 1 \\ 180^\circ & K^P > 1 \end{cases} \tag{44}$$

Prediction $DCPA^P$ risk membership function is:

$$u(dCPA^P)=\begin{cases}1 & dCPA^P \le \lambda \\ \frac{1}{2}-\frac{1}{2}\sin[\frac{\pi}{dCPA_0-\lambda}(dCPA^P-\frac{dCPA_0+\lambda}{2})], & \lambda < dCPA^P \le dCPA_0 \\ 0 & dCPA^P > dCPA_0\end{cases} \quad (45)$$

Prediction $TCPA^P$ risk membership function at next time is:

$$t_1^P=\frac{\sqrt{(d_l^{P\,2}-\lambda^2)}}{v_s^P} \quad (46)$$

$$t_2^P=\frac{\sqrt{(d_m^{P\,2}-dCPA_0{}^2)}}{v_s^P} \quad (47)$$

$$u(tCPA^P)=\begin{cases}1 & tCPA^P \le t_1^P \\ \frac{t_2^P-tCPA^P}{t_2^P-t_1^P}, & t_1^P < tCPA^P \le t_2^P \\ 0 & tCPA^P > t_2^P\end{cases} \quad (48)$$

According to the fuzzy comprehensive evaluation method:

$$CR_4=A\cdot B^P=(w_d,w_\theta,w_{dCPA},w_{tCPA})\cdot\begin{bmatrix}r_d^P \\ r_\theta^P \\ r_{dCPA}^P \\ r_{tCPA}^P)\end{bmatrix} \quad (49)$$

Collision risk CR_4 at next time is:

$$CR_4=[w_d u_d^P+w_\theta u_\theta^P+w_{dCPA}u_{dCPA}^P+w_{tCPA}u_{tCPA}^P] \quad (50)$$

4.5 Hybrid collision risk calculation method based on prediction

In section 4.3 and section 4.4 we have explained how to compute CR_3 and CR_4. In this section based on these computations we use our hybrid technique again. The proposed technique utilizes both CR_3 and CR_4 in order to obtain the better prediction results. The algorithm is based on steps depicted in figure 4.11.

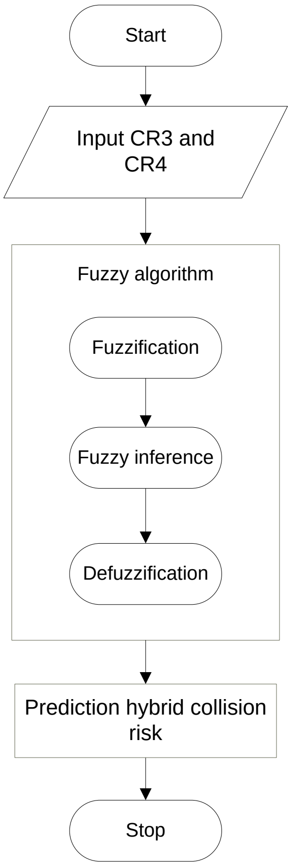

Figure 4.11: Flowchart of HCR^P calculation among vessel

Once we have computed the values for CR_3 and CR_4 we need to know which collision risk is better in order to obtain that we have introduce a fuzzy function to compute the HCR^P by combining CR_3 and CR_4. Table 4.3 depicts the rules for the fuzzy function.

There are five linguistic values for the variables prediction hybrid collision risk at next time as be shown in table 4.3.

Table 4.3: Range value of CR_3, CR_4 and prediction hybrid collision risk

CR_3	Value	CR_4	Value	HCR^P	Value
0-0.4	Low	0-0.4	Low	0-0.4	Low
0.2-0.6	Medium Low	0.2-0.6	Medium Low	0.2-0.6	Medium Low
0.4-0.8	Medium	0.4-0.8	Medium	0.4-0.8	Medium
0.6-1.0	Medium High	0.6-1.0	Medium High	0.6-1.0	Medium High
0.8-1.0	High	0.8-1.0	High	0.8-1.0	High

The fuzzy reasoning rule tables, in case when CR_3 of next time is L, ML, M, MH and H can be expressed in the forms of tables 4.4.

Table 4.4: Reasoning rule of degree of prediction hybrid collision risk

HCR^P		CR_3				
		L	ML	M	MH	H
CR_4	L	L	L	ML	M	MH
	ML	L	ML	ML	M	MH
	M	ML	ML	M	M	MH
	MH	M	M	M	HL	H
	H	MH	MH	HH	H	H

In our case the reasoning can be expressed in linguistic rules of two-input-one-output system as figure 4.12. CR_3 and CR_4 are the process state variables, prediction HCR is the control variable. Here, we generated 25 rules for prediction HCR of our proposed system:

```
1. If (CR3 is L) and (CR4 is L) then (PredictionHCR is L) (1)
2. If (CR3 is L) and (CR4 is ML) then (PredictionHCR is L) (1)
3. If (CR3 is L) and (CR4 is M) then (PredictionHCR is ML) (1)
4. If (CR3 is L) and (CR4 is MH) then (PredictionHCR is M) (1)
5. If (CR3 is L) and (CR4 is H) then (PredictionHCR is MH) (1)
6. If (CR3 is ML) and (CR4 is L) then (PredictionHCR is L) (1)
7. If (CR3 is ML) and (CR4 is ML) then (PredictionHCR is ML) (1)
8. If (CR3 is ML) and (CR4 is M) then (PredictionHCR is ML) (1)
9. If (CR3 is ML) and (CR4 is MH) then (PredictionHCR is M) (1)
10. If (CR3 is ML) and (CR4 is H) then (PredictionHCR is MH) (1)
11. If (CR3 is M) and (CR4 is L) then (PredictionHCR is ML) (1)
12. If (CR3 is M) and (CR4 is ML) then (PredictionHCR is ML) (1)
13. If (CR3 is M) and (CR4 is M) then (PredictionHCR is M) (1)
14. If (CR3 is M) and (CR4 is MH) then (PredictionHCR is M) (1)
15. If (CR3 is M) and (CR4 is H) then (PredictionHCR is MH) (1)
16. If (CR3 is MH) and (CR4 is L) then (PredictionHCR is M) (1)
17. If (CR3 is MH) and (CR4 is ML) then (PredictionHCR is M) (1)
18. If (CR3 is MH) and (CR4 is M) then (PredictionHCR is M) (1)
19. If (CR3 is MH) and (CR4 is MH) then (PredictionHCR is H) (1)
20. If (CR3 is MH) and (CR4 is H) then (PredictionHCR is H) (1)
21. If (CR3 is H) and (CR4 is L) then (PredictionHCR is MH) (1)
22. If (CR3 is H) and (CR4 is ML) then (PredictionHCR is MH) (1)
23. If (CR3 is H) and (CR4 is M) then (PredictionHCR is MH) (1)
24. If (CR3 is H) and (CR4 is MH) then (PredictionHCR is H) (1)
25. If (CR3 is H) and (CR4 is H) then (PredictionHCR is H) (1)
```

Figure 4.12: All rules in case of hybrid collision risk prediction

We designed the membership functions for CR_3, CR_4 and prediction hybrid collision risk at next time in our proposed solution. Figures 4.13 and 4.14 are displaying the fuzzy membership functions graphically and figure 4.15 is displaying the fuzzy membership function of degree graphically.

Figure 4.13 shows the membership function of CR_3. CR_3 is defined by 5 linguistic variables using membership functions as shown in section 4.3, which are defined between 0 and 1. In this figure the x-axis is the CR_3 input variable.

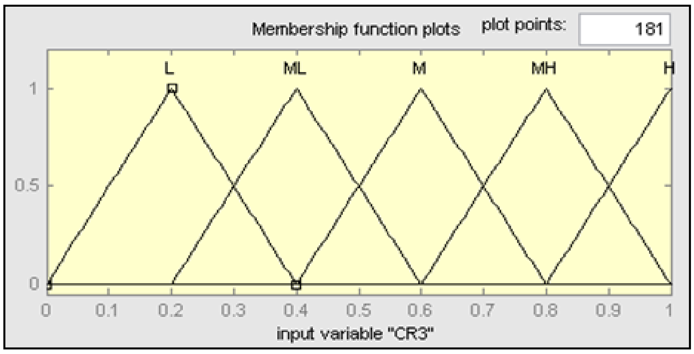

Figure 4.13: Membership function of CR_3

CR_4 is also defined by 5 linguistic variables using membership functions as shown in figure 4.14, which are same defined between 0 and 1. In this figure the x-axis is the CR_4 input variable.

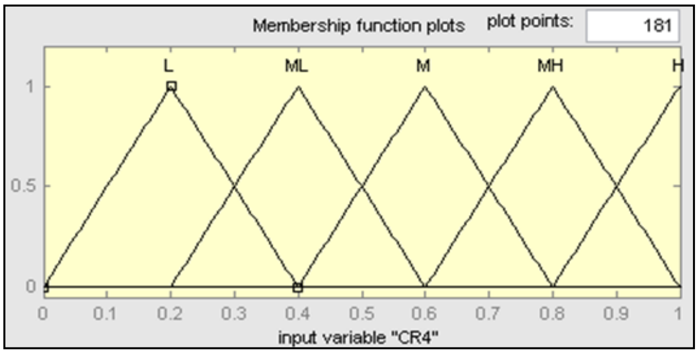

Figure 4.14: Membership function of CR_4

Figure 4.15 shows the membership function of prediction HCR. The reasoning fuzzy table to determine prediction HCR is provided using CR_3 and CR_4 as shown in table 4.4. Prediction HCR is defined between 0 and 1.

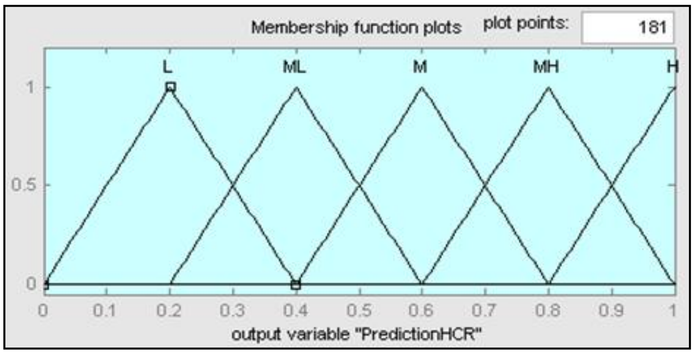

Figure 4.15: Membership function of degree of prediction hybrid collision risk

4.6 Simulation and performance

4.6.1 Simulation environment

The simulation is carried out with our designed simulator for the proposed system. The environmental configuration remains the same for all the experiments. The uniform configuration helps in the comparison of results with existing techniques. We developed the simulator by using .Net programming environment with the configuration shown in table 3.5.

4.6.2 Simulation results and performance analysis

We discussed the three scenarios i.e. head on, overtaking, and crossing in section 3.5.3 to test the performance of the system. The prediction based collision avoidance system is tested with the same three scenarios. We recorded the prediction results of each scenario. Figure 4.16 shows the head on situation where the own and target ships are crossing each other with the constant angle but the navigating towards each other. This situation is called head on because the both the ship are moving towards each other. Figure 4.21 shows the overtaking scenario where one ship is overtaking the other ship with the same angle but with a higher speed. Figure 4.26 shows the crossing scenario where two ships are expected to cross each other at a certain point. The direction, speed and target location are different, however the route of two ships intersect at certain point. Figure 4.17, 4.19 and 4.21 explains performance comparison between prediction hybrid collision risk, prediction fuzzy collision risk and prediction evaluation collision risk for three presented scenarios respectively. We will explain the results of each scenario in subsequent sections.

4.6.2.1 Head-on prediction scenario

In this scenario, the proposed system predicts the position of ship in the next time stamp and takes the control decision ahead of the reaching to higher risk location. The procedure of collision risk calculation remains the same as discussed in chapter 3. However the collision risk is calculated at the next position of the ship. This prediction helps in taking decision in advance and leads to better collision avoidance.

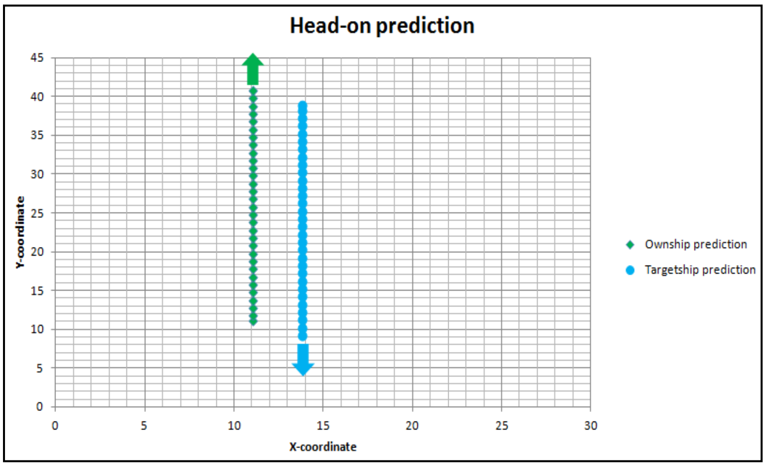

Figure 4.16: Navigation of head-on prediction

Figure 4.17 shows the risk values for head on situation shown in figure 4.16. It is evident from the figure 4.16 that the ships are moving with a constant speed and the direction of the ship remains the same. However the two ships are moving in opposite direction on different routes. The two routes are nearby each other; therefore the collision risk exists at the point where the two ships are crossing from the same region at the same time. Besides the collision risk is calculated the fuzzy system, therefore the collision risk is in real number and not a categorical/nominal value. The risk factor is ranging between 0 and 1, where 0 means the no risk and 1 means maximum risk of collision. Besides we compare CR_1, CR_2, CR_3, and CR_4 with prediction and without prediction. Figure 4.17 shows the comparison of CR_1, CR_2 and our proposed technique HCR. It is evident from the figure that HCR is more realistic risk for the head on situation shown in figure 4.16. The collision risk in the scenario situation start from the 0.45 and increased linearly as the two ships are approaching each other, however the collision risk become uniform when the two ships were passing through the conjunction area. The figure also shows that the collision risk linearly decreased when the two ships passed by each other as the direction of the two ships are opposite to each other. It is also clear from the figure that the CR_1 and CR_2 are varied in a non linear fashion which does not reflect the realistic risk of the scenario. Therefore it is pertinent to mention that the HCR calculates a more practical collision risk for head on situation.

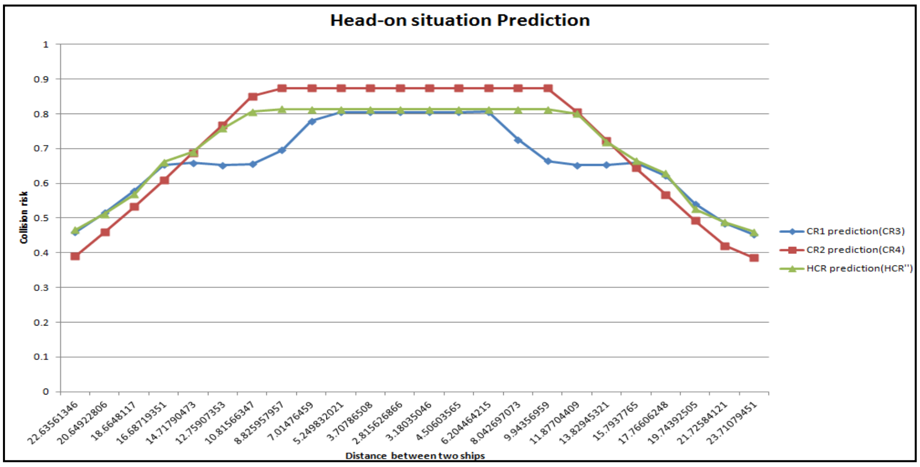

Figure 4.17: Simulation result of prediction for head-on scenario

Figure 4.18 shows the comparison of CR_1 without prediction and CR_1 with prediction (CR_3) for the head on situation. It is clear from the figure that the CR_3 is more practical for the scenario shown in figure 4.16. The CR_1 fluctuates at different points, however the CR_3 remains linear.

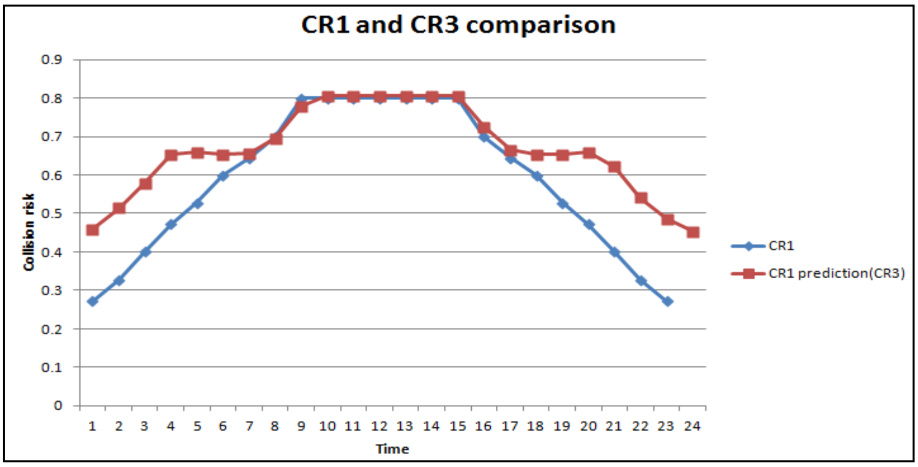

Figure 4.18: Comparison of CR_1 and CR_1 prediction of head-on situation

Figure 4.19 shows the comparison of CR_2 and CR_2 prediction (CR_4). From this figures we can see the prediction collision risk values is greater than non prediction collision risk values, it means the collision risk of next position is under a better control and the ship will not reach to the higher collision risk position.

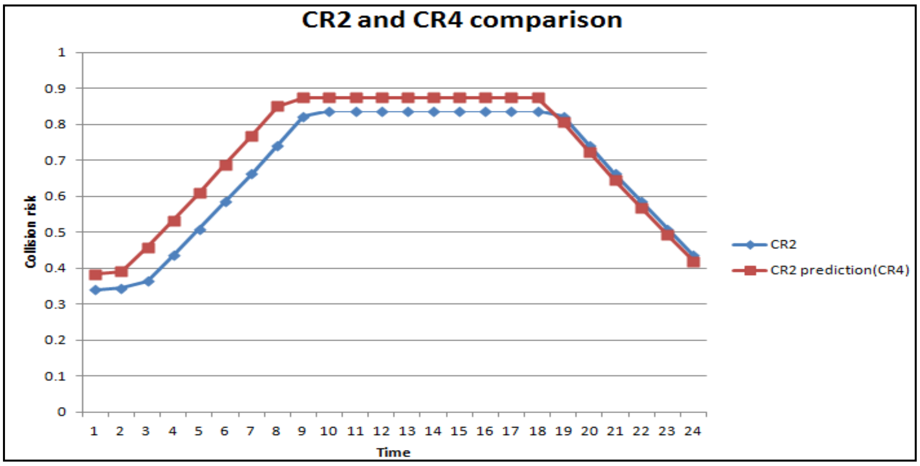

Figure 4.19: Comparison of CR_2 and CR_2 prediction of head-on situation

Figure 4.20 shows the comparison of our proposed approach (HCR) in the presence of prediction and without prediction. The figure shows that the collision risk without prediction is higher during the recorded duration; it is because of the reason that the collision risk is controlled ahead of approaching to the point of higher risk.

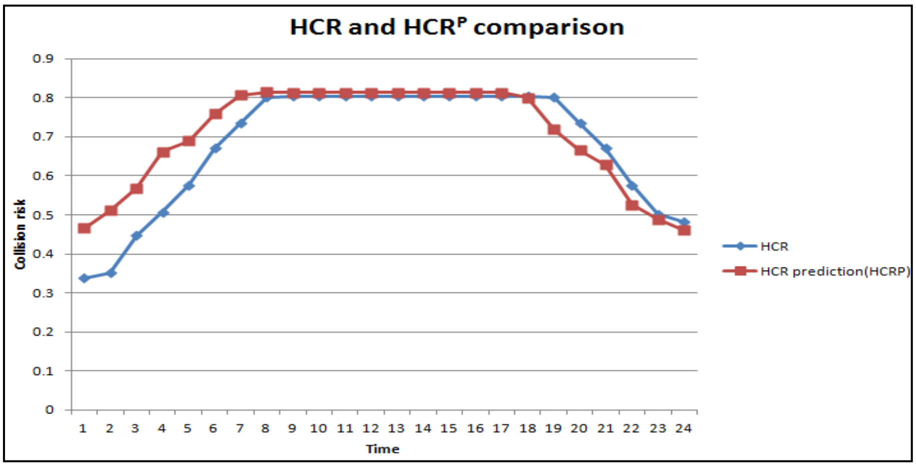

Figure 4.20: Comparison of HCR and HCR prediction in head-on situation

4.6.2.2 Overtaking prediction scenario

The overtaking scenario for prediction of collision risk comparison is shown in figure 4.21. The figure shows that one ship is overtaking another ship having faster speed. The routes of the two ships are also shown in the figure.

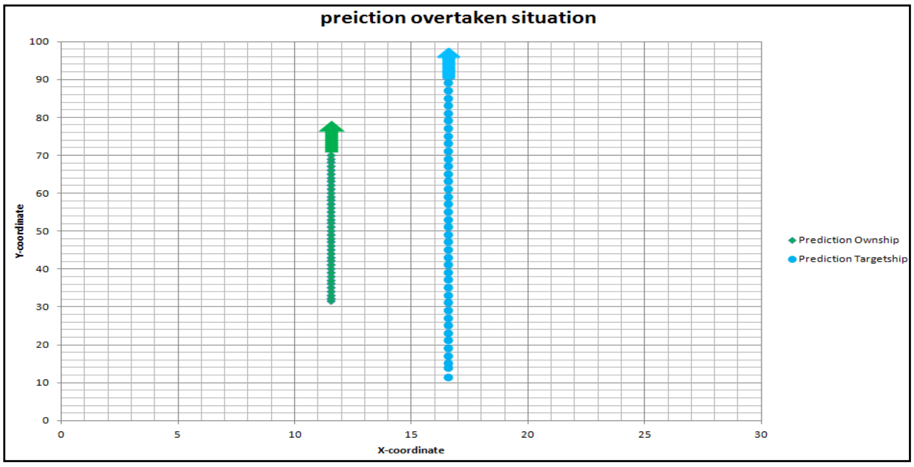

Figure 4.21: Diagram of navigation of overtaking prediction

In figure 4.22 it show the variation of prediction hybrid collision risk, prediction collision risk based on fuzzy and prediction collision risk based on fuzzy comprehensive evaluation. In figure 4.21, it is evident that the collision risk increased linearly as the two ships are approaching each other. When the target ship overtaking own ship at a certain distance, the prediction collision risk is uniform for till the target ship crossed the own ship. However, when the own ship is overtaken by target ship the prediction collision risk is decreased linearly. The results show that prediction hybrid collision risk performance better than other techniques.

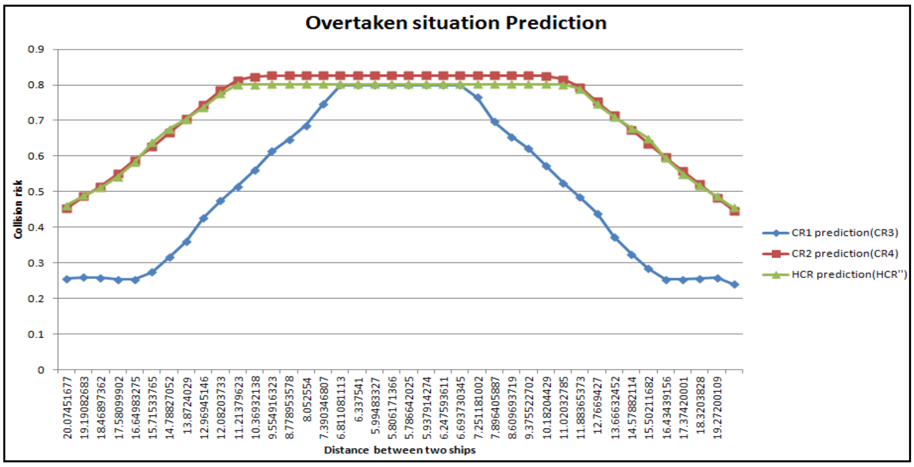

Figure 4.22: Simulation results of overtaking scenario

Figure 4.23, 4.24 and 4.25 shows the comparison of CR_1 and CR_1 prediction value, CR_2 and CR_2 prediction value and HCR and prediction HCR value respectively. From these figures, it is clear that the collision risk with prediction is bigger than collision risk without prediction. It means that the navigation is not controlled ahead of time and the collision risk is reached to the threshold and then the controller is invoked, however in the presence of prediction the ship is controlled ahead of approaching to the threshold collision risk and the collision risk is always controlled within a range to avoid collision accident.

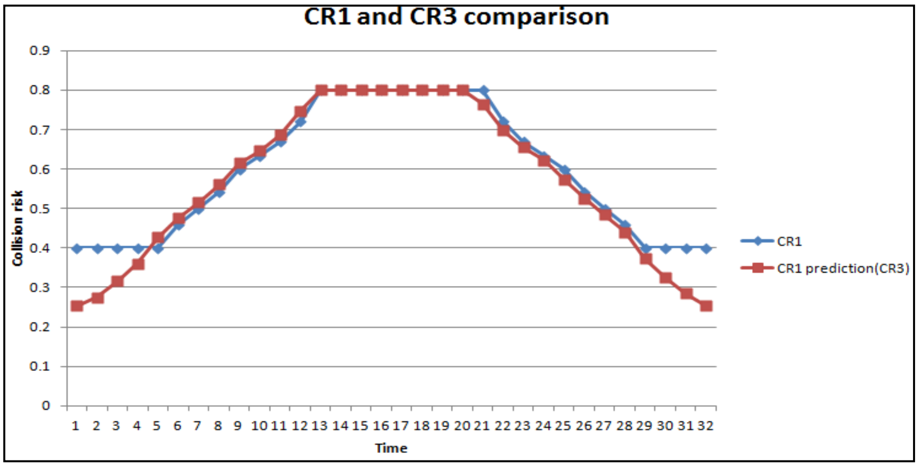

Figure 4.23: Comparison of CR_1 and CR_1 prediction of overtaken situation

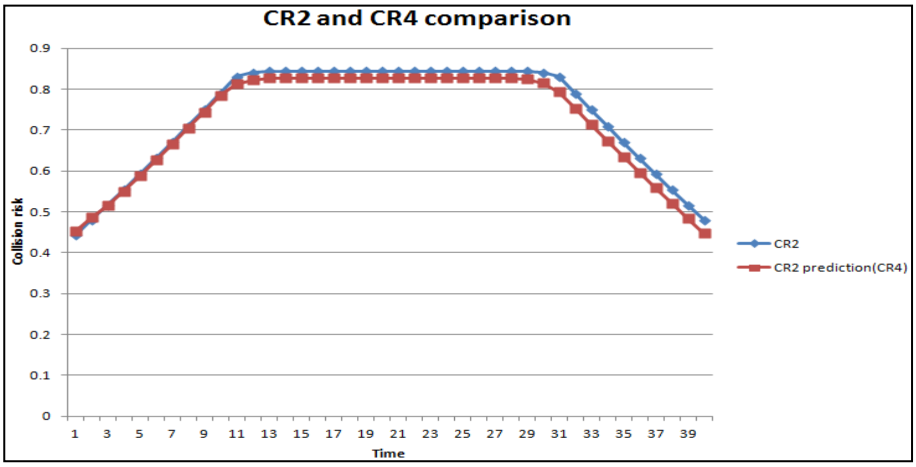

Figure 4.24: Comparison of CR_2 and CR_2 prediction of overtaken situation

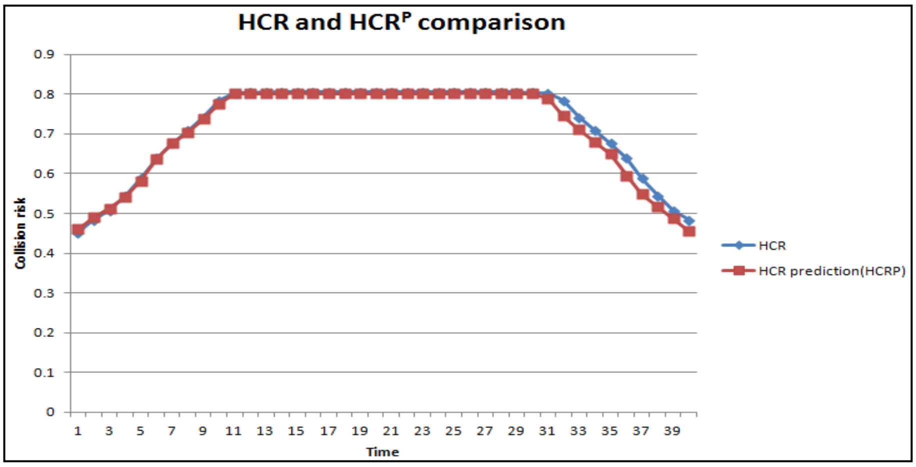

Figure 4.25: Comparison of HCR and HCR prediction of overtaken situation

4.6.2.3 Crossing prediction scenario

The crossing scenario is shown in figure 4.26. The figure shows the target and own ships have different routes, however the two ships will cross the same position at the same time, so there is a chance of collision at the crossing point. We performed the simulation and recorded the results. The prediction based collision avoidance results of own and target ship is shown in figure 4.27.

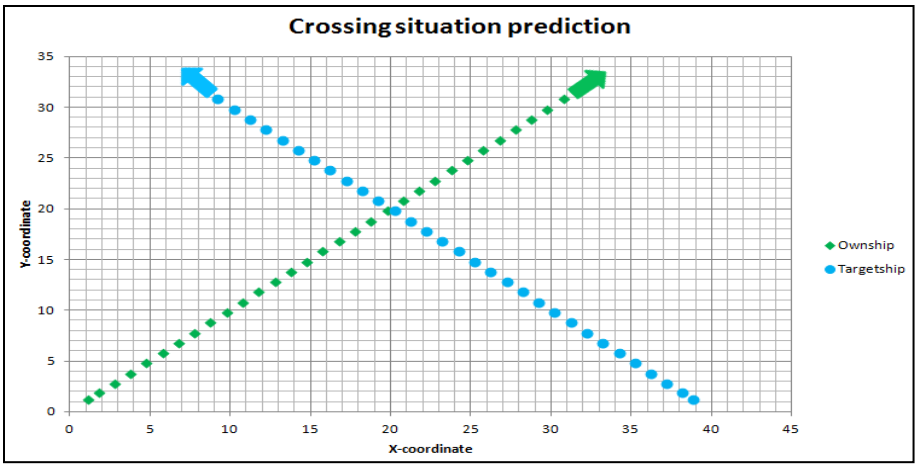

Figure 4.26: Diagram of navigation of crossing prediction

Figure 4.27 shows that the collision risk is minimum in the beginning of the simulation; however as the two ships navigates towards the destination they were approaching to the crossing point and hence the collision risk increases. It is clear from the figure that the collision risk of our technique HCR is pragmatic for the scenario shown in figure 4.26. Because the prediction results shows that when the own and target ship come closer, the risk value is increased. After two ships crossed and started going away from each other the prediction risk start decreasing.

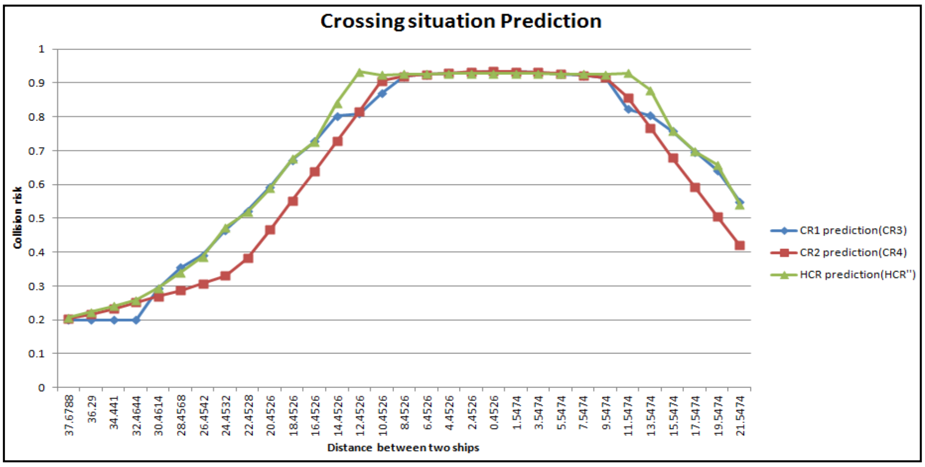

Figure 4.27: Simulation results of prediction based collision risk calculation for crossing scenario

Figure 4.28, 4.29 and 4.30 shows the comparison of CR_1 and CR_1 collision risk, CR_2 and CR_2 collision risk and HCR and prediction HCR collision risk in the crossing situation shown in figure 4.26. From these figures it is clear that the prediction based collision risk is more pragmatic and could increase the collision avoidance efficiency.

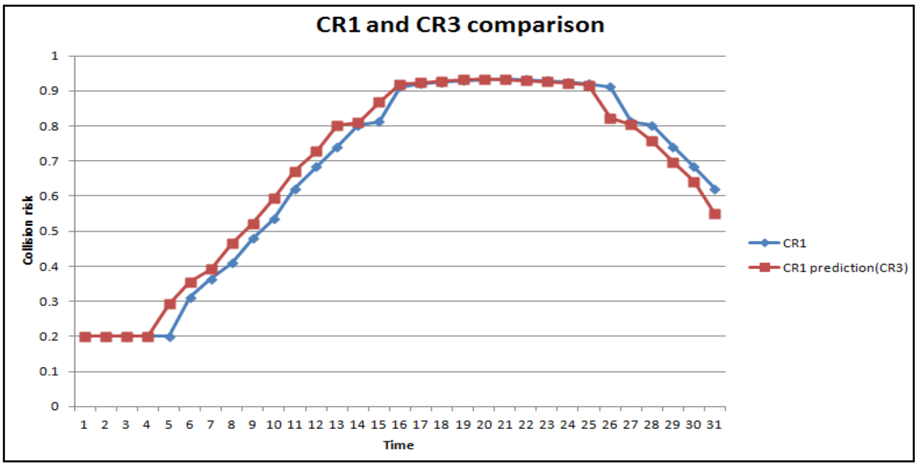

Figure 4.28: Diagram of comparison of CR_1 and CR_1 prediction of crossing situation

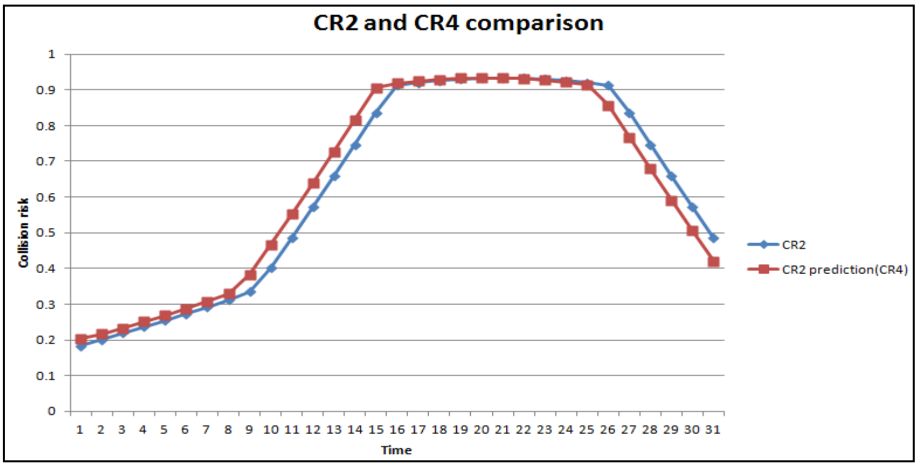

Figure 4.29: Comparison of CR_2 and CR_2 prediction of crossing situation

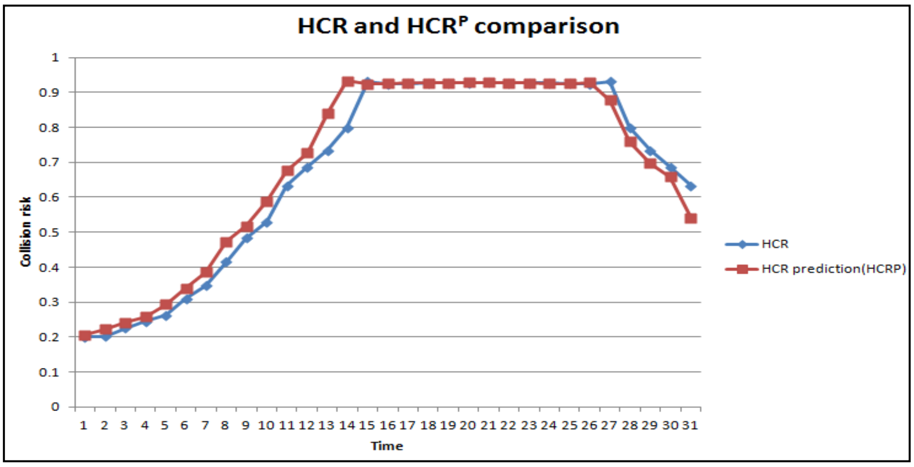

Figure 4.30: Comparison of HCR and HCR prediction of crossing situation

5. Ship control based on collision risk

5.1 Proposed ship control algorithm

When determining the collision risk of current time and next time, it is necessary to judge the encounter situation of each ship. Encounter situation can be identified using two angles between own ship and target ship as shown in figure 5.2.

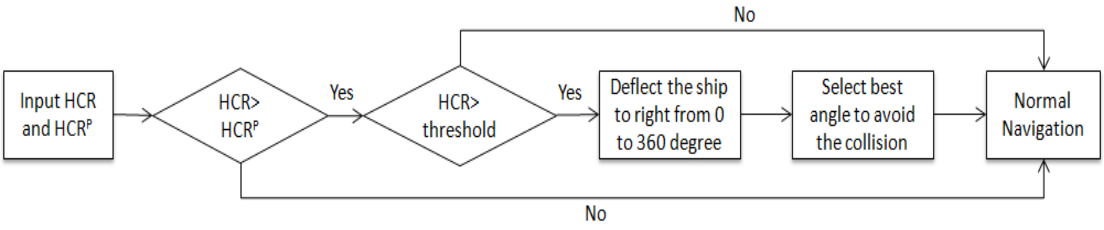

Figure 5.1: Ship control using collision risk of proposed system

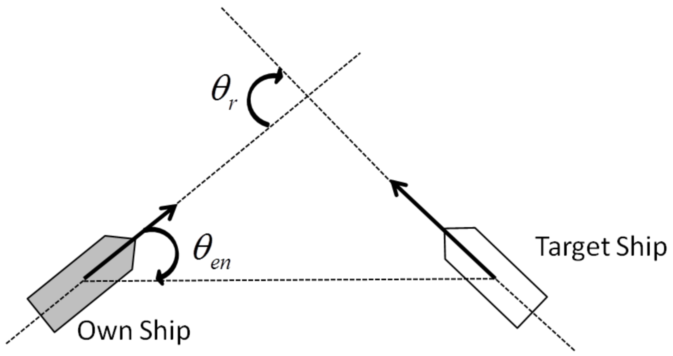

Figure 5.2: Relative angle and encounter angle

Figure 5.1 shows the control module of proposed system and figure 5.3 elaborate the flowchart of avoidance process of each vessel. Before the ship start, avoiding control module will compare the collision risk HCR at current time and HCR^P at next time. If HCR is bigger than HCR^P, it means the collision risk of next time is lower and if the ship keeps the current state it will avoid the dangerous situation. On contrary, if HCR^P is bigger than HCR, it means the collision risk at next time is higher. So we need to take action to avoid the collision accident. Our proposed system will avoid the collision due to the change in the angle of vessel. The ship will start avoiding when HCR^P is equal or greater than the threshold value. In simulation system threshold was set as 0.6.

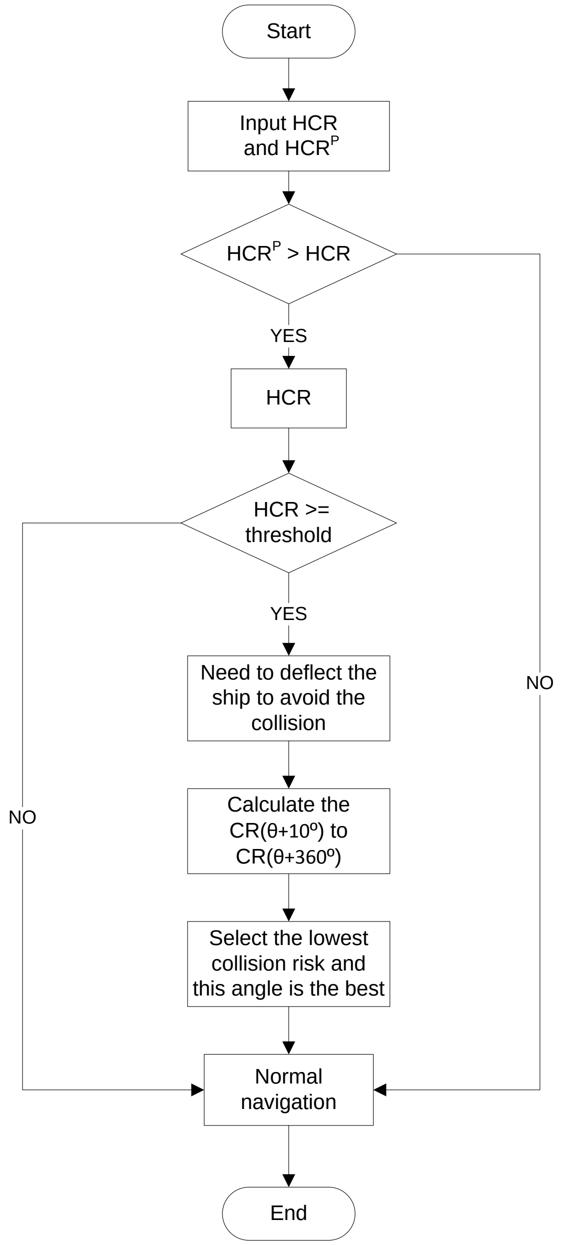

Figure 5.3: Flowchart of Avoidance of each vessel

After detecting the collision risk, we reach to the criteria where each ship will take a collision avoidance action as described in figure 5.4.

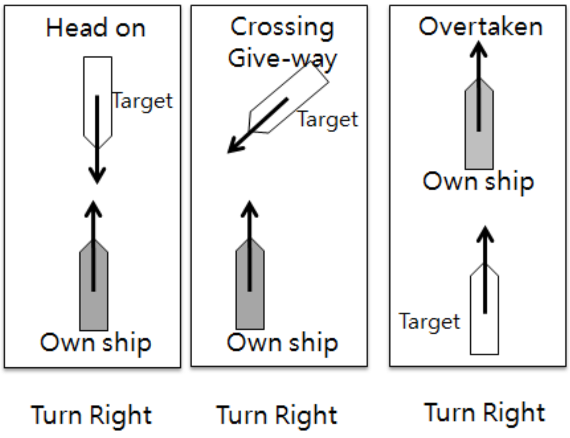

Figure 5.4: Encounter situation and avoidance actions

Once avoiding mode started, the ship will take avoiding action normally by turning right. The angle of ship change will be determined by present heading angle minus the course change angle θ_d which is chosen 10 degree. We will calculate the collision risk again based on the course change angle. If the collision risk is bigger, the module will turn right the ship to change the course angle again until the collision risk become smaller. Furthermore, in this simulation, before deflecting the angle of vessel we calculate the collision risk from θ_d =10 to θ_d =360 and all the collision risk will be list to show the mariner and they will choose the best deflection angle to deflect the vessel by avoiding the collision risk.

5.2 Simulation and performance analysis

5.2.1 Simulation environment

To validate the proposed avoidance algorithm, we developed the simulator which using .Net programming environment with the configuration is shown in table 3.5.

5.2.2 Simulation results and performance analysis

We discussed the three scenarios to test the proposed avoidance algorithm of the system as shown earlier in figure 3.25, 3.27 and 3.29. The control of ship based on comparison of hybrid collision risk and hybrid collision risk prediction. We recorded the results of control in each scenario. We assume the own ship and the target ship are moving with the same speed 3m/s in head-on and crossing situation. In overtaken situation we assume that the own and target ship are moving with different speed 3m/s and 4m/s respectively.

Figure 5.5 shows the variations of collision risk in each time stamp in case of head-on situation. The collision risk in the head-on situation start from 0.34 and increased linearly as the two ships are approaching each other without control. However, when the collision risk between ships bigger than 0.6, our proposed collision avoidance control module control the navigation angle of each ship to decrease the collision risk and avoid own ship and target ship collision.

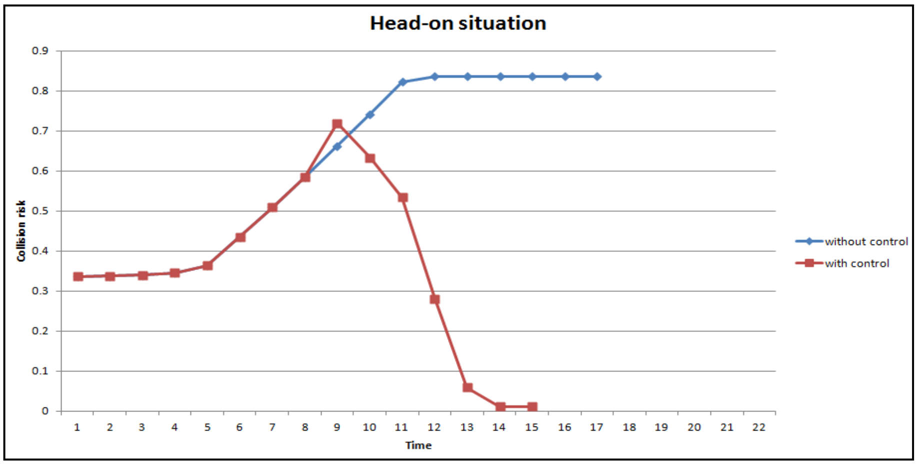

Figure 5.5: Diagram of collision risk variation with control in head-on situation

In figure 5.5 the blue curve shows the collision risk without control and red curve shows the collision risk with control. After the direction of that time was changed the distance between two ships was become shorter the collision risk did not decreased, but increased persistently. Due to the collision avoidance control module the ship was controlled continually, the collision risk decreased linearly. It is clear from the figure that the collision risk decreased with control of ship's navigation.

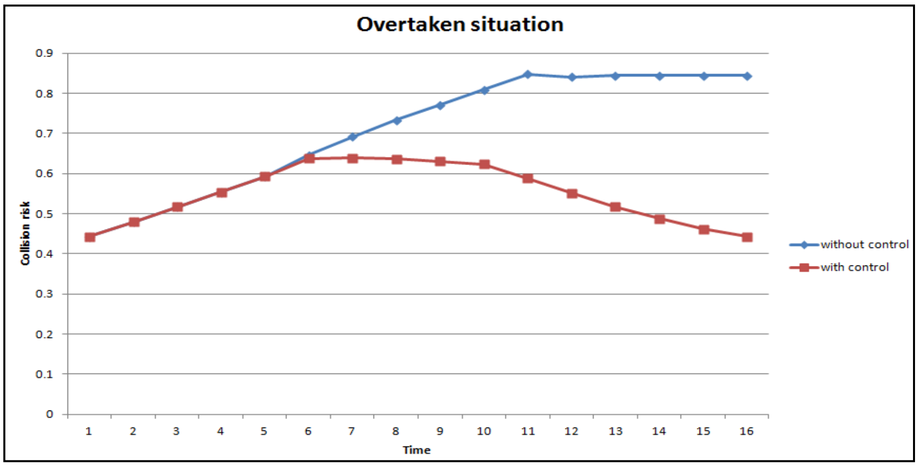

Figure 5.6: Diagram of collision risk variation with control in overtaken situation

Figure 5.6 shows the variations of collision risk in each time stamp in case of overtaken situation. The collision risk in this scenario start from 0.44 and increased linearly as the two ships are approaching each other without control. When our proposed collision avoidance control module detects the collision risk between ships bigger than 0.6, the navigation angle of each ship is controlled in order to decrease the collision risk. Figure 5.6 shows the blue curve and red curve that present the collision risk without control and the collision risk with control respectively. In the control of proposed collision avoidance control module, the collision risk decreased. It is clear from the figure that the collision risk decreased with control ship.

Figure 5.7 shows the variations of collision risk in each time stamp in case of crossing situation. In this scenario the collision risk start from 0.19 and increased linearly as the two ships are approaching each other without control. After applied our proposed collision avoidance control module as long as the collision risk between ships bigger than 0.6, in order to reduce the collision risk the system change the navigation angle of both ships. The collision risk of ships decreased by proposed collision avoidance control module continually until the collision risk is in the normal range. It is clear from the figure that the collision risk decreased with control.

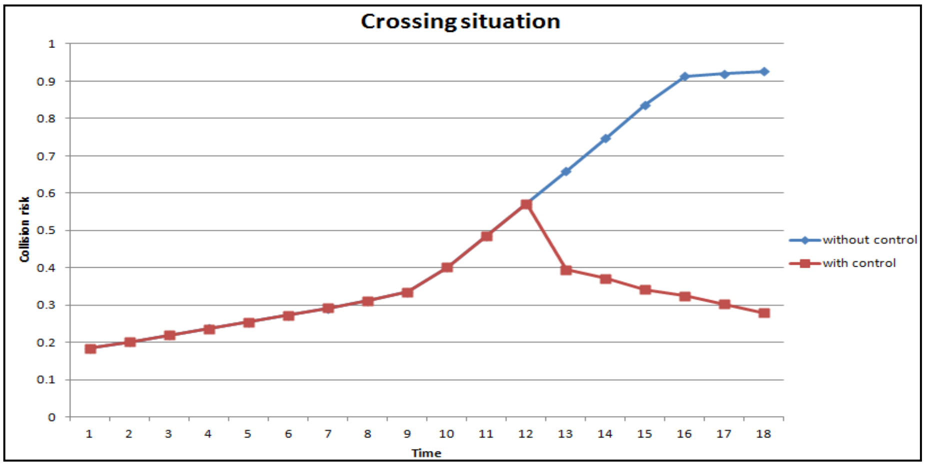

Figure 5.7: Diagram of collision risk variation with control in crossing situation

From the three scenarios we tested the collision risk variation results of with control and without control. The figure 5.5, 5.6 and 5.7 shows that in the control of proposed collision avoidance control module the collision risk decreased effectively. Our proposed collision avoidance control module change the navigation angle of the own and target ship in order to avoid the collision with each other as long as the collision risk is bigger than threshold value. Furthermore, our proposed collision avoidance control module calculate the collision risk between ships after each ship deflect the angle from 10 to 360 degree and calculate the collision risk of each divided angle. In addition, this module also selects the best deflection angle of each ship to avoid the collision and send it to mariners.

6. Conclusions

This dissertation has presented a method for automatic hybrid collision risk calculation of current time, prediction hybrid collision risk of next time and collision avoidance to control ship to be used in an automatic navigation simulation system.

In this research work, we described the approach of hybrid collision risk calculation which combines the theories of fuzzy logic, fuzzy comprehensive evaluation and the conventional risk calculation techniques in order to enhance the accuracy of existing research. In additional, we present a hybrid collision risk prediction using Kalman Filter. Based on this method we develop a system that calculate the current time hybrid collision risk and also predict the hybrid collision risk of next time. According to the results of comparison we know the collision risk at next position is high or low. Besides, we also proposed the method that give the best action in advanced to prevent the collision accident when there is a collision possibility. To make the easy understandability of the proposed approach three scenarios has been presented in this dissertation. Experiments have been performed in order to test quality of the proposed system.

However, much work is required to incorporate the knowledge and skills of experienced mariners so that the actions of the system can resemble those of human pilots more closely. The simulation program in its current form does have some limitations. For example, the weather conditions are not taken into consideration; it does not have any optimization or prediction ability and also the developed algorithm has not been tested in complex navigational situations.

References

Hasegawa, K, “Automatic Collision Avoidance System for Ship Using Fuzzy Control”, Journal of the Kansai Society of Naval Architects, 10p, Issue Number: No.205, ISSN: 0389-9101, 1987.

Q.Xu & X.Meng,N.Wang, “Intelligent Evaluation System of Ship Management”, international journal on Marine Navigation and safety of Sea Transportation, volume 4, Number 4, 2010.

史国友 & 贾传荧, “航海模拟器中 DCPA TCPA 的算法”, Juournal of Dalian Maritime University, Vol.25, No.3, 1999.

Ahmad C.Bukhari, Inara Tusseyeva, Byung-Gli lee & Yong-Gi Kim, “An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system”, Expert Systems with applications, pp.1220-1230, 2013.

Jing-Hyeong Ahn, Key-Pyo Rhee & Young-Jun You, “A study on the collision avoidance of a ship using neural networks and fuzzy logic”, Applied Ocean Research, Volume 37, pp.162-173, 2012.

Kazuhiko Hasegawa & Junji Fukuto, “An Intelligent ship handling simulator with automatic collision avoidance function of target ships”, INSLC 17- International Navigation Simulator Lecturers’ Conference, Rostock-Warnemuende, 2012.

Mingkui Feng & Yongjin Li, “Ship Intelligent Collision Avoidance based on Maritime Police

Warships Simulation System", pp.293-296, 2012.

Q.Xu, X.Meng & N.Wang, "Intelligent Evaluation System of Ship Management", the international Journal on Marine Navigation and Safety of Sea Transportation, Vol.4, No.4, pp.479-482, 2010.

Nobuo Mitomo & Kenjiro Hikida, "A few comments on visual system of ship handling simulator based on arriving port", IEEE International Conference, pp.1890-1894, 2008.

Tohoko Koike & Tadatsugi Okazaki, "Development of ship simulator system for designing auto-pilot", World Automation Congress (WAC), pp.1-5, 2010.

Jianghua Sui, "An AND-OR Fuzzy Neural Network, Ant Colony Optimization - Methods and Applications", Avi Ostfeld (Ed.), ISBN: 978-953-307-157-2, 2011.

Andrzej S.Lenart, "Manoeuvring to required approach parameters – distance, time and bearings", ANNUAL OF NAVIGATION, 2000.

FUJII, Y, et al.: Effective Areas of Ships (in Japanese). J. JIN (35), pp.71-76, 1966.

FUJII, Y.: Effective Collision Diameter and Collision Rate of Ship (in Japanese). J. JIN (41), pp.31-39, 1969.

Alaa Damen Shtay & Wahed Gharib, "An Intelligent Control system for ship collision avoidance", International Journal of Engineering & Technology IJET, pp.36-41, Vol.9, No.10.

Alan C.Schultz, "Using a genetic algorithm to learn strategies for collision avoidance and local navigation", Reprinted from the Proceedings of the Seventh International Symposium on Unmanned Untethered Submersible Technology, University of New Hampshire Marine Systems Engineering Laboratory, September 23-25, 1991, pp.213-215.

Yanzhuo Xue & D.Clelland, “Automatic simulation of ship navigation”, Ocean Engineering, Vol.38, Issues 17-18, pp.2290-2305, 2011.

Guedes Soares C. & Teixeira A.P, “Risk assessment in maritime transportation”, Reliability Engineering and System Safety, 74: 299-309, 2001.

Gaarder S. et al, “Impact of human element in marine risk management”, Advances in safety and reliability pp. 857-868, 1997.

WU Zhao-lin & ZHENG Zhong-yi, “Time collision risk and its model”, Journal of Dalian Maritime University, 27(2): 1-5, 2001.

Fuji J. & Tanaka K, “Traffic Capacity”, The Journal of Navigation 24(4): 543–552, 1971.

Davis P. V. et al, “A Computer Simulation of Marine Traffic Using Domains and Areas”, The Journal of Navigation, 33(2): 215-222, 1980.

Kearon J, “Computer programs form collision avoidance and traffic keeping”, Conference on mathematical aspects of marine traffic. London, pp. 229-242, 1979.

Imazu H. & koyama T, “Determination of times of collision avoidance”, The Journal of Japan Institute of Navigation, 70: 30-37, 1984.

LI Li-na et al, “A Summary of Studies on the Automation of Ship Collision Avoidance Intelligence”, Journal of Jimei University (Natural Science), 11(2):188-192, 2006.

HASEGAWA, K, “Automatic Collision Avoidance System for Ship Using Fuzzy Control”, Proc. Eighth Ship Control Systems Symposium (SCSS) (2), 34-58, 1987.

FUKUTO, J., K. HASEGAWA, R. MIYAKE and M. YAMAZAKI, “Ship Handling Simulator for Assessing Onboard Advanced Navigation Support Systems and Services”, Introduction of Intelligent Ship Handling Simulator, Proc. MARSIM 2012, 2012.

Ren, Y, Mou, J, Yan, Q., & Zhang, F, “Study on assessing dynamic risk of ship collision. Multimodal approach to sustained transportation system development, Information, technology, implementation”, In Proceedings of 1st international conference on transportation information and safety, pp. 2751-2757, 2011.

Okazaki, T., Koike, T., Hirai, Y., & Kayano, J, “Development of ship simulator system for designing auto-pilot”, In World automation congress (WAC), 2010.

Smierzchalski, R., & Michalewicz, “Adaptive modeling of a ship trajectory in collision situations at sea”, IEEE Transactions on Evolutionary Computation, 3,227-241, 2000.