Dissertation for Doctor of Engineering

A Study on Development of Expert System for Collision Avoidance and Navigation Based on AIS

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Abstract

Nowadays, highly increasing global trade has caused heavy traffic in the main sea routes. Moreover, ships are getting larger and larger in size, faster in speed and highly specialized. Under these circumstances, serious collision accidents between ships happened at sea over and over again, and led to not only huge loss of life and property but also serious damage to marine environment.

Meanwhile, due to the high level of economic growth, more and more people tend to choose their jobs in land rather than them aboard ships. Therefore, their competence as navigation officers becomes worse now than in the past. Even so decision-making during navigation entirely depends on the experience and knowledge of responsible officers or shipmasters aboard. During navigation, decision-making made by them can

determine the fate of own ship and the ships in the vicinity of her. However, the number of experienced navigation officers or shipmasters is far less than that of the world fleet. New seafarers can not absorb and comprehend such precious experience in a short time. In order to adequately utilize the experience and effectively reduce collisions at sea, an expert system for collision avoidance and navigation (hereinafter called "ESCAN") is proposed in this paper. As a method to come up with the low competence of new seafarers, the ESCAN can provide them with reasonable recommendations of collision avoidance or can help them to know better about current traffic situation and make more reasonable decisions of collision avoidance when dangerous situations happen.

Some equipment like radar/ARPA can provide a very simple function for collision avoidance. However, the information obtained from such equipment can not effectively help new seafarers to make reasonable decision-making of collision avoidance in a short time, and they need more helpful information and instructions of collision avoidance.

On the other hand, with use of AIS technology, the ESCAN developed in this paper can receive more useful navigational information of other ships in the vicinity of own ship and can provide more sophisticated recommendations or suggestions for dealing with current situation.

The following are conclusions from this study.

Firstly, COLREGS, the process of collision avoidance and some other related aspects are discussed here. Some results are given as follows:

(1) In order to prevent and avoid collisions at sea, and to secure safe navigation of ships, COLREGS needs to be correctly comprehended and strictly carried out.

(2) Safe speed is a primary factor ensuring if own ship has enough time to determine and take proper and effective avoidance actions. During navigation, it should be appropriately determined so as to adapt to prevailing circumstances and conditions.

(3) Safe passing distance should be maintained during navigation. Normally in open sea two(2) nautical miles are considered to be sufficient.

(4) Encountering process of two ships can be divided into 4 phases such as phase of effect-free action, phase of involving risk of collision, phase of involving close-quarters situation and phase of involving danger of collision.

(5) Usually, navigators use value of collision risk to know the risk of collision and to select the primary target to avoid. In ESCAN, formula (2-2) is used to appraise the value of collision risk.

(6) If own ship is involved in a multi-target encountering situation, ESCAN will analyze the encountering situations between own ship and other ships, predict possible movement of other ships, determine which target is the primary one to avoid, and determine avoiding action and the time to take. Meanwhile,

navigators should also consider the safe passing distance of current situation and the safe zone of collision avoidance provided by ESCAN. By using this approach, appropriate decision-making for dealing with current multi-target encountering situation of can be acquired.

Secondly, detailed design of ESCAN is introduced and some results can be drawn as follows:

(1) The ESCAN is designed and developed by using the theory and technology of expert system and based on information provided by AIS and radar/ARPA system.

(2) It is composed of four components. Facts/Data Base in charge of preserving data from navigational equipment, Knowledge Base storing production rules of the ESCAN, Inference Engine deciding which rules are satisfied by facts, User-System Interface for communication between users and ESCAN.

(3) In ESCAN, AIS technology is used. AIS can help own ship to receive more detailed navigational information from the ships in the vicinity of her. Therefore, more reasonable decision-making can be determined according to such abundant information.

(4) Navigational knowledge used in ESCAN is based on COLREGS and other navigation expertise.

(5) Module structure is used to build the knowledge base of ESCAN. And it is divided into six modules such as basic navigational rules module, maneuverability judgment module, division of encountering phase module, encountering situation judgment module, auxiliary knowledge of collision avoidance module, and navigation experience and multi-ship encountering scene avoiding action module.

(6) Production rules are used to represent the knowledge of collision avoidance in ESCAN because the structure of them is perfect for representing such knowledge and they are supported by CLIPS well.

(7) A new inference process of collision avoidance as shown in Fig.3-8 is used in ESCAN.

(8) Mixed inference which combines forward inference and backward inference is used in ESCAN.

(9) Because CLIPS adopts Rete Pattern-Matching Algorithm, response speed of ESCAN is greatly increased.

Finally, detailed implementation of ESCAN is introduced and some conclusions are given as follows:

(1) The part of ESCAN in charge of inference is programmed in CLIPS and the remaining part of it is programmed in Visual C++.

(2) The ESCAN has the function of real-time analysis and judgment of various encountering situations between own ship and targets, and is to provide navigators with appropriate plans of collision avoidance and additional advice and recommendation.

(3) Auxiliary functions of ESCAN are convenient for users such as simulation function which can simulate avoiding actions provided by ESCAN.

(4) According to the results of the examples, the suggestions provided by ESCAN conform to the rules of COLREGS and the advice given by navigation experts well.

(5) It is easy to upgrade ESCAN when rules are required to be upgraded in the future. Only rules in Knowledge Base should be rewritten rather than the whole system.

(6) Multi-target encountering case matching function of ESCAN can provide a recorded reference case for dealing with current situation if all the conditions of the case are matched.

Development of ESCAN not only can help navigators make more reasonable decision-making of collision avoidance so as to ensure safe navigation of ships, but also can promote the development of integrated automatic navigation system which integrates all shipborne systems and implements intelligent unmanned navigation. The future study will deal with integrating ESCAN with other shipborne systems and make it more user-friendly and will carry out the experiment on board which is the important part of ESCAN.

AIS 기반 충돌회피 및 항해 전문가시스템 개발에 관한 연구

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초 록

오늘날 무역량의 급속한 증가로 세계 주요 항로에서의 해상 교통량은 폭주하고 있다. 더욱이 선박은 대형화와 함께 고속화 되고 있으며 또한 전용화가 이루어 지고 있다. 이런 환경으로 해상에서의 선박 충돌 사고 계속 발생하고 있어 이런 충돌로 인하여 인명 및 재산에 큰 손해를 발생할 뿐만 아니라 심각한 해상 오염을 발생하기도 한다.

한편, 높은 수준의 경제 성장에 따라 사람들은 승선 근무를 기피하게 되어 항해자의 직무 능력은 과거에 비하여 떨어져 있는 편이다. 그런데도 불구하고 항해 중의 의사 결정은 전적으로 책임 항해사의 경험과 지식에 의존하고 있다. 항해사 혹은 선장이 취한 의사 결정은 자신의 선박과

주위의 선박의 운명을 결정하게 된다. 그러나 경험이 많은 선장 및 항해사의 수는 선박 척수보다는 훨씬 적다. 신규의 항해사들은 짧은 시간에 그런 값진 경험들을 습득할 수가 없다. 이런 경험을 적절하게 이용하여 해상에서의 충돌을 효과적으로 줄이기 위하여 이 논문에서는 충돌 회피 및 항해 전문가 시스템(expert system for collision avoidance and navigation, ESCAN)을 제안한다. 신규 항해사들의 낮은 능력을 보완하기 위한 하나의 방법으로 ESCAN 은 충돌 회피에 관한 합리적인 권고를 항해사들에게 제시하여 현재의 교통 상황을 더 이해하게 하고 충돌의 위험이 발생할 때 충돌 회피에 관한 합리적 의사 결정을 하게 한다.

레이더/ARPA 와 같은 장비는 충돌 회피에 관한 단순한 기능을 제공하여 이들 장비에서 나타난 정보는 짧은 시간에 충돌 회피의 의사 결정을 하는데 효과적이지 못하여 충돌 회피에 관한 정보 및 지시 등이 더 필요하게 한다.

한편 AIS 기술 활용하여 이 논문에서 개발한 ESCAN 은 본선 주위에 있는 상대 선박에 관한 보다 유용한 항해 정보를 받을 수 있어 현재의 상황을 처리하는데 보다 나은 권고나 제안을 할 수 있다.

이 논문에서 얻은 결론은 다음과 같다.

먼저 해상충돌방지규칙(COLREGS)와 충돌회피과정, 그와 관련된 내용을 검토하였으며 그 내용은 다음과 같다.

(1) 해상에서의 충돌을 예방하고 선박의 안전 항해를 확보하기 위해서

COLREGS 를 정확하게 이해하고 엄격하게 따라야 한다.

(2) 안전 속력은 효과적인 충돌 회피 동작을 결정하고 취하는데 충분한 시간을 확보하는 1 차적인 요소이다. 항해 중 그 상황에 맞는 속력을 적절하게 유지하여야 한다.

(3) 항해 중 안전한 통과 거리를 확보하여야 하는데 대양 항해에서는 통상 2 마일로 간주한다.

(4) 양 선박이 조우할 때 과정은 충돌 회피 동작의 효과가 없는 단계, 충돌의 위험성이 있는 단계, 극한 상황에 있는 단계, 충돌 위험(거의 충돌하는) 단계 등으로 나눌 수 있다.

(5) 통상 항해사들은 충돌의 위험이 제일 큰 선박을 결정하는데 충돌위험도 값을 사용한다. ESCAN 에서는 공식 (2-2)를 이용하여 충돌위험도를 평가한다.

(6) 본선이 여러 선박과 조우할 때 ESCAN 은 본선과 상대 선박과의 조우 상황을 분석하여 각 선박의 가능한 움직임을 예측한다. 또 어떤 선박을 제일 먼저 피할 것인지 정하고 각각의 선박에 대하여 안전한 충돌 회피 동작 및 시간을 결정한다. 한편 항해사는 현재 상황에 대한 안전 통과 거리를 고려하여 ESCAN 에서 제공한 안전 충돌 회피 영역(방위, 속력)이 적절한지를 확인한다. 이런 방법을 이용하여 현재의 다수의 선박의 조우 상황에 대하여 적절한 의사 결정을 할 수 있다.

두 번째로 ESCAN 을 설계하고 개발하였는데 그 결과는 다음과 같다.

(10)ESCAN 은 전문가 시스템의 이론과 기술을 이용하여 설계하고 개발하였으며 AIS, 레이더/ARPA 정보를 기반으로 하였다

(11)ESCAN 은 항해 장비의 데이터를 보존하는 데이터베이스(Facts/Data Base), ESCAN 의 프로덕션 룰을 저장하는 지식베이스(Knowledge Base), 데이터에 알맞은 규칙을 결정하는 추론기구(Inference Engine), 사용자와 ESCAN 과의 통신을 위한 사용자-시스템 인터페이스(User -System Interface) 등으로 4 가지로 구성되어 있다.

(12)ESCAN 에서는 AIS 기술을 사용한다. AIS 는 본선이 본선 주위에 있는 상대 선박에 관한 상세한 항해 정보를 제공한다. 그러므로 이를 이용하면 의사 결정을 보다 합리적으로 할 수 있다

(13)ESCAN 에 사용된 항해 지식은 COLREGS 및 항해 전문가의 지식을 기반으로 한 것이다.

(14)ESCAN 의 지식 베이스는 모듈 구조로 되어 있으며 그 내용은 기본 항해 규칙 모듈, 조종 평가 모듈, 조우 단계 구별 모듈, 조우 상태 판단 모듈, 추가 충돌 회피 지식 모듈, 항해 경험 및 다수의 선박의 회피 모듈 등의 6 개의 모듈이다.

(15)프로덕션 룰을 ESCAN 에서 충돌 회피에 관한 지식을 표현하는데 사용하였다. 그 이유는 프로덕션 룰의 구조가 이런 지식을 완전하게 표현할 수 있고 또 CLIPS 언어로 잘 지원될 수 있기 때문이다.

(16)ESCAN 에 사용된 충돌 회피에 관한 새로운 추론 과정은 그림 3-8 과 같다.

(17)ESCAN 은 전향추론과 후향추론을 혼합한 형태를 사용하였다.

(18)CLIPS 는 레터 패턴 매칭 알고리즘을 사용하므로 ESCAN 의 반응 속도는 상당히 향상되었다.

마지막으로 ESCAN 을 실험하여 다음과 같은 결과를 얻었다.

(1) ESCAN 의 추론 부분은 CLIPS 로 프로그램 되어 있지만 나머지 부분은 비쥬얼 C++로 되어 있다.

(2) ESCAN 은 본선과 상대 선박이 조우하는 여러 가지 상황에 대하여 실시간으로 분석하고 판단하는 기능을 가지고 있으며 항해사들에게 적절한 충돌 회피 계획, 충고, 혹은 권고 등을 제공한다.

(3) 또 ESCAN 은 사용자가 충돌 회피 동작을 시뮬레이션 할 수 있는 기능을 가지고 있다.

(4) 이 연구에서 제시한 몇 가지 예를 따르면 ESCAN 은 COLREGS 규칙을 따르고 있으며 아울러 항해 전문가의 조언을 따르고 있다.

(5) 장차 규칙을 추가하고자 할 때 추가 업그레이드가 가능하다. 이것은 전 시스템을 고치는 것이 아니라 지식 베이스에 사용된 규칙만을 다시 쓰면 되기 때문이다.

(6) 다수 선박의 조우 상황에서는 모든 조건을 만족하는 현재의 상황을

처리할 수 있는 표준 케이스를 제공하고 있다.

ESCAN 의 개발은 항해사가 합리적인 판단을 하는데 도움을 주어 안전 항해를 하게 할 뿐만 아니라 항해 장비를 통합하여 무인 항해가 가능한 통합자동항법시스템의 개발까지 연계될 수 있다. 앞으로 다른 항법시스템과 통하여 사용자에게 편리한 시스템을 구성하는 연구가 남아 있으며, 또 실선에서의 실험을 통하여 ESCAN 을 보완하는 연구가 남아 있다.

Chapter 1 Introduction

1.1 Background and Purpose of the Study

In the 21st century, the global economy develops fast, and the volume of international trade also increases sharply. As an intermediate industry, shipping industry also develops very fast. In the past few decades, large-sized and high-speed trends in ships became obvious, the number of ships of world fleets increased quickly. Therefore maritime traffic situation especially in the main sea routes became worse. Although the development of technologies of shipbuilding and navigation was rapid and the improvement of shipborne navigation equipment was remarkable, serious collision accidents of ships still happened again and again, and caused not only huge loss of life and property of nations and individuals, but also serious pollution of maritime environment [2].

In China, in recent years, as the relevant statistic data indicate, collision accidents account for more than 40% of all marine traffic accidents. And the collisions caused by human errors occupy almost 80% of all collisions. In Korea, similar statistic data are also found, according to the recent report of Korean Maritime Safety Tribunal (KMST[1)]), in 2003~2007, a total of 1598 accidents happened in Korean costal waters. Among these accidents, collision accidents are

[1)] Since 1963, the Korean maritime Safety Tribunal (KMST) has been committed to ensuring safety at sea by investigating all types of marine accidents and determining their circumstances and causes. The KMST is a subsidiary body of the Ministry of Land, Transport and Maritime Affairs (MLTM) under the Marine Accident investigation and Tribunal Act.

1059 cases and occupy 66.27%. And among the 1059 collisions, the ones caused by human errors are 863 cases and occupy 81.49% of all collisions or 54.01% of all accidents [24]. And the detailed situation of these accidents happened in Korean coastal waters is shown in Fig.1.

From the above figures, we can see that if the human errors can be dealt with well, the majority of these collision accidents could have been avoided [33]. So it is significant and urgent to research how to deal with the human errors so as to reduce these collisions [41].

Generally speaking, the human errors can be dealt with by two kinds of approaches.

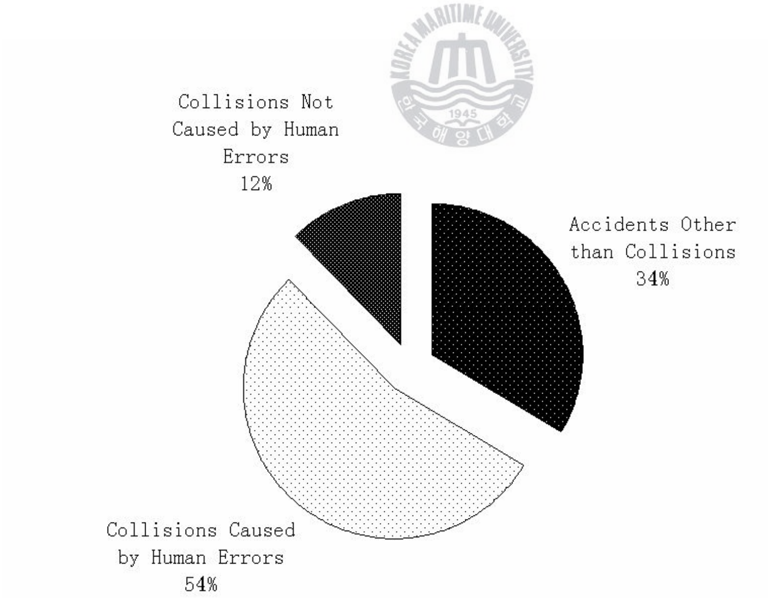

Fig.1-1 Statistic of Maritime Accidents in Korean Waters (2003~2007)

(1) To strengthen training and management of the crew, improve quality of them, and enhance their sense of responsibility [44].

In order to improve quality of the crew and reduce the accidents caused by human errors, IMO[2] constituted STCW78[3]. The STCW78 has strong constraining force to seafarers and tries to improve the quality of them. But due to the high level of economic growth, many people recently think that working aboard ships is a tough job and they have a less preference for becoming crew. Therefore, their competence as crew becomes worse now than in the past. And this leads to that new seafarers' experience of collision avoidance is insufficient and they also can not skillfully operate shipborne equipment and so on. These problems seriously affect the navigation safety of ships. Nowadays, in the field of practical collision avoidance of ships, the task of collision avoidance still lies on decision-making of navigators. In the past, because the traffic density and speed of ships are not so high, such task can still be effectively undertaken by subjective judgments and manual manoeuvres of navigators. However, nowadays, ships become bigger and faster, this approach obviously becomes no longer appropriate for this task.

(2) To improve the level of automatization of shipborne equipment and gradually implement navigation automatization.

With the rapid development of science and technology, the level of automatization of shipborne equipment has increased quickly. To implement an

[2] IMO (International Maritime Organization), formerly known as the Inter-Governmental Maritime Consultative Organization (IMCO), is a late 20th century creation. The IMO promotes cooperation among governments and the shipping industry to improve maritime safety and to prevent marine pollution.

[3] STCW78 (International Convention on Standards of Training, Navigational Certification and Watchkeeping for Seafarers, 1978) sets qualification standards for masters, officers and watch personnel on seagoing merchant ships.

automatic decision-making system for dealing with collision avoidance is a perfect approach to effectively reduce the effect of human errors and alleviate the burden of navigators. Ordinarily, radar/ARPA[4)] is the main shipborne equipment for collision avoidance, and it can provide some basic information of collision avoidance, for example *DCPA*[5)] and *TCPA*[6)] of detected targets. However, it is easily affected by environment. So it can not satisfy the requirements of modern navigation. More advanced technologies which can assist navigators in accomplishing the task of collision avoidance are required.

So far, no satisfied solution which can effectively reduce labor intensity and alleviate psychological burden of navigators so as to reduce collisions is found. In order to solve this problem, many countries began to research and develop automatic decision-making system for collision avoidance. In the last decade, due to significantly practical value of this topic, it became a hot topic.

As a method to reduce collision accidents of ships at sea, an Expert System for Collision Avoidance and Navigation (ESCAN) is proposed in this paper. The ESCAN is designed and developed by using theories and technology of expert system, knowledge of COLREGS[7)] and other navigation expertise. And it is based on the information provided by AIS[8)] receiver and radar/ARPA. The ESCAN has the function of real-time analysis and judgment of encounter situations between

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4) A maritime radar with Automatic Radar Plotting Aid (ARPA) capability can create tracks using radar contacts. The system can calculate the tracked object's course, speed and closest point of approach (CPA), thereby knowing if there is a danger of collision with the other ship or landmass.

5) DCPA: Distance to Closest Point of Approach.

6) TCPA: Time to Closest Point of Approach.

7) The International Regulations for Preventing Collisions at Sea 1972 (COLREGS) are published by IMO, and set out the "rules of the road" to be followed by ships and other vessels at sea.

8) The Automatic Identification System (AIS) is a system used by ships and Vessel Traffic Services (VTS) principally for identification and locating vessels.

own ship and targets, and of providing reasonable plans of collision avoidance. Moreover, with the help of advice and recommendation given by ESCAN, navigators can easily acknowledge each collision situation and improve their judgment of it.

1.2 Introduction of AIS

IMO and maritime authorities have paid much attention to the issue of ship's safe navigation. IMO constitutes COLREGS and regulates that ships need to carry navigation equipment compulsively. Moreover, in order to manage ships and keep them navigating safely, VTS centers are built and ship reporting system is implemented. However, ship collision accidents still happened again and again. Some equipment such as radar/ARPA has a basic function of collision avoidance. However, a lack of positive identification of the targets on the displays, and time delays and other limitation of radar for observing and calculating the action and response of ships around, especially on busy waters, sometimes prevent possible action in time to avoid collision. In order to solve the problem, IMO, IALA[9] and ITU[10] cooperate and provide a performance criterion of AIS. While requirements of AIS are only to display very basic text information, the data obtained can be integrated with a graphical electronic chart or a radar display, providing consolidated navigational information on a single display. And the configuration of

[9] T IALA International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) is a non-profit organization to collect and provide nautical expertise and advice.

[10] The International Telecommunication Union (ITU) is an international organization established to standardize and regulate international radio and telecommunications.

AIS system is shown in Fig.2.

AIS provides a means for ships to electronically exchange ship data including: identification, position, heading, course, and speed, with other nearby ships and VTS station. This information can be displayed on a screen or an ECDIS display. AIS is intended to assist the vessel's watchstanding officers and allow maritime authorities to track and monitor vessel movements. It works by integrating a standardized VHF transceiver system with an electronic navigation system, such as a LORAN-C[11] or GPS[12] receiver, and other navigational sensors on board ship (gyrocompass, rate of turn indicator, etc.)

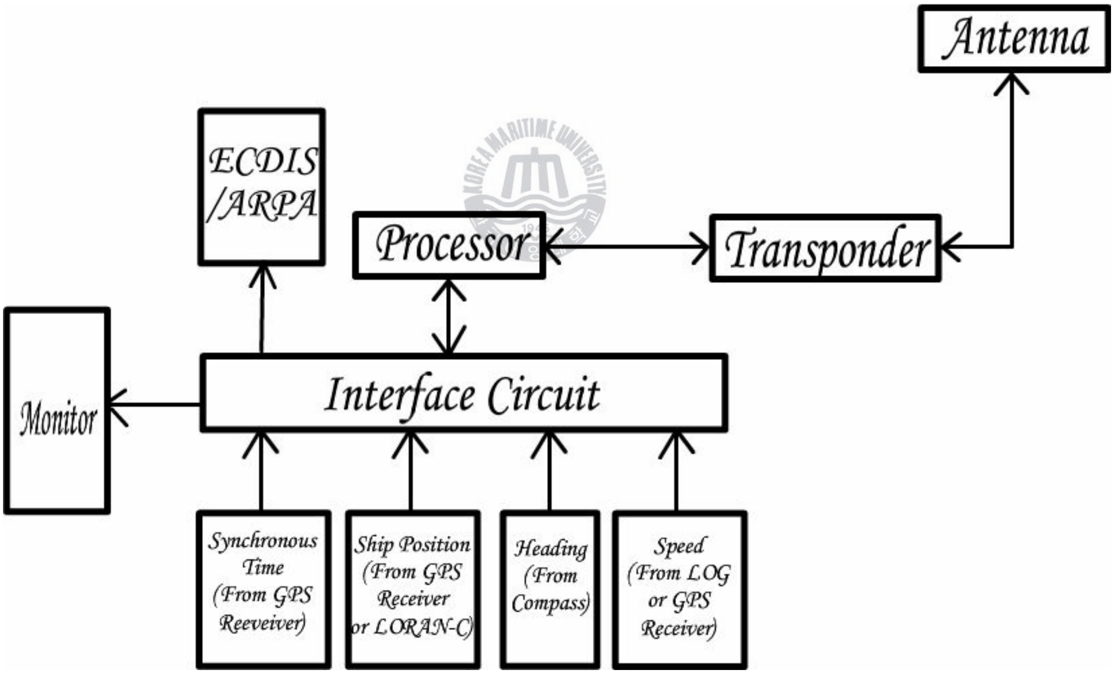


Fig.1-2 Configuration of AIS

[11] LORAN(LOng Range Aid to Navigation) is a terrestrial radio navigation system using low frequency radio transmitters that uses multiple transmitters to determine location and/or speed of the receiver. The current version of LOREN in common use is LORAN-C, which operates in the low frequency portion of EM spectrum from 90 to 110 kHZ.
[12] The Global Positioning System (GPS) uses a constellation of between 24 and 32 Medium Earth Orbit satellites that transmit precise microwave signals that enable GPS receivers to determine their current location, the time and their velocity (including direction).

The IMO International Convention for the Safety of Life at Sea (SOLAS) requires AIS to be fitted aboard international voyaging ships with gross tonnage (GT) of 300 or more tons, and all passenger ships regardless of size. It is estimated that more than 40,000 ships currently carry AIS class A equipment.

If all ships carry AIS equipment, ships can send out their navigational information and can receive navigational information from other ships in the vicinity of them. Identification of other ships will no longer be a problem. This technology is a new means of lookout and greatly favorable for management of ships. One more important aspect is that AIS technology can provide more important information even including the purpose of actions of other ships. So navigators can acquire more valuable information and reduce the disharmony in the actions of own ship and other ships [26].

Generally speaking, the specialties of AIS are as follows:

(1) AIS can provide more detailed information of detected targets, for example heading of a target.

(2) The information received from AIS receiver is more accurate and reliable. And no 'mis-tracking' problem exists because all data come from sensors of other ships.

(3) AIS can provide real-time data.

(4) AIS works in an autonomous and continuous mode.

(5) This technology can reduce disharmony in the actions of own ship and other ships.

(6) AIS is almost not effected by weather and sea conditions. Medium for data

transferring is stable. And no blind area exits at close quarters.

1.3 Introduction of Expert System and CLIPS

An expert is a person who has a very high level of knowledge in a certain field or subject. In the field of navigation of ships, navigators and masters who have abundant navigational experience are experts of this field.

Expert system is a branch of AI (artificial Intelligence) that makes extensive use of specialized knowledge to solve problems at the level of a human expert [9]. And it is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solutions. That is, an expert system is a computer system that emulates the decision making ability of a human expert [8]. So ESCAN is a program that attempts to perform in all aspects like one or more experienced human navigation experts.

CLIPS (C Language integrated Production System) is one of the most popular expert system languages. It is developed by Johnson Space Center of NASA, and is written in C language. The first version was produced in 1985, and the latest version is CLIPS 6.24.

CLIPS is a complete environment for developing expert system which includes features such as an integrated editor and a debugging tool. CLIPS is a rule-based language, and only supports forward chaining rules. Because efficient RETE pattern-matching algorithm is used in CLIPS, response speed of systems programmed in CLIPS is fast. A program written in CLIPS may consist of rules and facts [6].

CLIPS is a higher-order language than languages like C because it is easier to do certain things, but there is also a smaller range of problems that can be addressed. That is, the specialized nature of expert system languages makes them suitable for writing expert systems but not for general purpose programming. In many situations, it is necessary to export itself to other language like Visual C++ for implementing convenient user-system interfaces and so on.

1.4 Related Studies of the Study

Automatic decision-making system for collision avoidance has been researched and developed for years. Some positive results of this field have been achieved in some studies. Among these studies, although some aspects are similar, no one is the same as ESCAN which is developed by using theory and technology of expert system and CLIPS as the tool of inference.

1.4.1 Related Studies in China

Yang from JIMEI University proposes an AI approach using theory of expert system, mathematical analysis, and fuzzy mathematics [44]. The approach can build a real-time and dynamic knowledge base of collision avoidance to implement optimum decision-making.

Qu from Dalian Maritime University proposes an automatic avoidance collision system using technology of computer and expert system, and knowledge of fuzzy mathematics [32]. The system can analyze the encounter of two ships at sea, and it can offer a reasonable precept to avoid collision, which settle the collision problem effectively and ensure the navigation safety.

Other similar studies [3], [4], [11], [12], [34], [43], [53], for example the one from Wuhan University [4], have also obtained some positive results in this field.

1.4.2 Related Studies in Other Countries

A study from Liverpool Industry University proposes an expert system containing a knowledge base for dealing with multi-target collision avoidance at open sea [34]. And the sources of knowledge of the system are COLRGES, explanations of COLRGES provided by navigation experts and good seamanship. In the system, encountering situations are divided into six types and the decisions for collision avoidance are sixteen types in all. During navigation, this advisory system can provide navigators with reasonable reference decisions for collision avoidance.

Another study from Tokyo University of Mercantile Marine proposes an automatic collision avoidance system which is a subsystem of 'Maritime Navigation Expert System' [34]. The system has not only hardware but also software which can directly give orders of engine and helm. It achieved good results.

K.Kose et al from Hiroshima University develop an integrated navigation system (INS) which is considered as a next generation navigation system [42]. This INS incorporates the developed Collision Avoidance Expert System as an intelligent decision-making support function to assist operators to avoid collision during ship navigation.

C.Yang et al from Canada incorporate a collision avoidance expert system into a real-time ship-handling simulator in order to provide intelligent decision-making support for navigation training [41]. And some good results are also achieved in this study.

1.4.3 Principal Research Method in the Related Studies

The procedure of principal research method in the related studies in 1.4.1 and 1.4.2 can be summarized as follows:

(1) To built a knowledge base for storing the knowledge collecting from COLERGS, navigation expertise of experts, maneuverability of own ship and various ships.

(2) To analyze the present state of own ship's movement and encountering situations between own ship and target ships.

(3) To search proper measures of collision avoidance in knowledge base. Or inference engine automatically provides appropriate decision-making by inferences based on relevant rules and information.

Generally speaking, three types of technologies are usually used to develop such automatic decision-making system for collision avoidance [36].

(1) Neural Network [35] [45]

This technology is a new discipline, but it has greatly influenced many disciplines such as computer science, AI and so on. It has a lot of advantages, but the inference process of it is hidden in the middle layer of it. So it is very hard to be understood. Nowadays, automatic decision-making system for collision avoidance totally implemented by neural network technology is quite rare.

(2) Fuzzy Control

It is a technology based on theories of fuzzy set and is a method of control by simulating the process of human fuzzy inference and decision-making. It is the most popular technology used in the related studies [14], [15], [28]. Fuzzy control system is based on fuzzy mathematics; and uses fuzzy format to represent knowledge; and uses fuzzy logic inference as theoretical basis. Fuzzy controller is the kernel of it.

(3) Intelligent Control of Expert System

It is a technology integrating theories of expert system and approaches of control. In an unknown environment, it can emulate the ability of a human expert and effectively control the system. A system based on this approach can quickly adapt various environments. During long-term operation, it can be highly reliable and works in real-time environment. It has a bright future on application of intelligent control and is arousing increasing attention from people. Usually, an expert system using this technology is composed of knowledge base, inference engine, database and data acquiring facility.

1.5 Scope and Content of the Study

Nowadays, collision accidents still happen again and again at sea. In order to improve such situation and ensure safe navigation of ships, it is necessary and important to research automatic decision-making system for collision avoidance. In this paper, as a method to reduce collision accidents at sea, ESCAN is proposed and implemented.

The scope of this study is to analyze related aspects of collision avoidance, and then according to the specialties of this field, to design the ESCAN which can provide real-time suggestions of collision avoidance based on the information from navigation equipment including AIS receiver, and then to use CLIPS and VC++ to implement the ESCAN including properly representing and storing the knowledge of this field, receiving real-time data, developing user-system interface and so on.

As to the content of this study, in Chapter 2, COLREGS, the process of collision avoidance and some related aspects are analyzed. In Chapter 3 and Chapter 4, the design and implementation of ESCAN are introduced respectively. Finally, conclusions of this study are given in Chapter 5.

Chapter 2 Analysis and Research of COLREGS and Collision Avoidance

2.1 COLREGS

2.1.1 Introduction of COLREGS

COLREGS are regulations for ensuring safe navigation of ships and for preventing collision accidents at sea. The constitution and implement of COLREGS greatly reduced occurrences of collisions, and provided both sides of a collision with legal foundation to divide civil responsibility. It greatly promotes the development of shipping industry. In order to keep up with the development of modern traffic management and navigation technologies, the 1972 Regulations came into force in 1977 and were amended in 1981,1987,1989,1993 and 2001 respectively [13].

Every regulation, term, shape, light, sound and light signal all came from practical cases of collision avoidance, especially the failed ones – collision accidents. COLREGS are summarized from the lessons of numerous collision accidents rather than from navigators' long-term experience of collision avoidance. Preventing collisions and ensuring safe navigation of ships is the most important premise for accomplishing various shipping tasks, and is the primary duty of seafarers on duty. In order to prevent and avoid collisions at sea, and to ensure safe navigation of ships, COLREGS need to be correctly comprehended and strictly carried out.

2.1.2 Content of COLREGS

The 1972 Regulations contains 5 parts, 38 rules and 4 annexes [5]. And contents of it are shown in Annex I.

2.1.3 Look-out

In COLREGS, look-out behavior is regulated in Rule 5 which is '*Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision.*'

In the field of collision avoidance, look-out is to observe the environment and traffic situation in the vicinity of own ship, especially to observe other ships and to know and judge the actions of them. 'Look-out' is a process for collecting and identifying the information of targets.

Keeping proper look-out is the primary factor of ensuring safe navigation. Statistically, a lot of accidents at sea were caused by improper look-out. So keeping proper look-out so as to detect other ships and judge their actions in time is a prior condition for judging encountering situations and adequately appraising the risk of collision. Look-out is not only to know and grasp current encountering situation, but also to pay attention to the developing trend of the situation. Every judgment lies on the result of look-out. So whenever, under any environment, crew of any ship should use any necessary method for look-out. Usually, proper look-out contains effective use of available equipment and instruments, in addition to sight and hearing. And the equipment and instruments are radar/ARPA, binoculars, VHF and AIS receiver and so on. The task of look-out is to report whether targets exist and navigational information of the detected targets.

2.1.4 Safe Speed

In COLREGS, safe speed is regulated in Rule 6 which is '*Every vessel shall at all times proceed at a safe speed so that she can take proper and effective action to avoid collision and be stopped with a distance appropriate to the prevailing circumstances and conditions.*'

COLREGS does not provide the quantified definition of 'Safe Speed'. But in COLREGS, it is implied that the safe speed should be enough for taking appropriate and effective action of collision avoidance, and should be enough for taking all way off in a proper distance according to the prevailing circumstances and conditions [38]. That is to say, in order to obey the rule, speed should be adjusted when environment or situations change.

Usually, safe speed can be explained as follows [50]:

(1) Ship proceeds at a speed so that she can have enough time for appraising

the situation at that time and taking proper and effective avoiding actions. Such speed can be considered as a kind of safe speed.

(2) Ship proceeds at a speed so that she can have enough time for taking proper and effective avoiding actions and taking all way off in a proper distance according to the prevailing circumstances and conditions. Such speed is also considered as a kind of safe speed.

Here, speed of (1) can be considered as the safe speed which can be used in good visibility conditions; speed of (2) can be seen as the safe speed which can be used in restricted visibility conditions. So according to (1) and (2), safe speed can be properly determined in any situation.

2.1.5 Risk of Collision

'Risk of Collision' is separately listed in Rule 7 of COLREGS, and is mentioned in Rule 5,8,12,14,15,18,and 19. But definition of 'Risk of Collision' is not regulated in COLREGS. The 1972 Conference rejected a proposed definition that 'risk of collision' exists between ships when their projected courses and speeds place them at or near the same location simultaneously. Had this definition been accepted a ship detecting another at long range, slowly approaching from the port side with little change of bearing, would have been obliged to keep her course and speed for a long period, possibly several hours.

'Risk of Collision', this term is rather flexible. In different environment, different ships or seafarers may get different understanding of it. It relates to many factors, such as *DCPA* and *TCPA* which are the most important two factors of them. *DCPA* is the only criterion for measuring whether two ships will collide. *TCPA* is a factor of judging the potential risk of collision between two ships. If *DCPA = 0*, it is to say two ship will collide if they both keep their speed and course respectively. If *DCPA >0*, it is to say that there is some distance for passing, but it does not mean two ships can pass safely. Unsafety means danger exists. So when *0 <= DCPA < safe passing distance*, risk of collision still exists. Considering *TCPA*, it is easy to find that the risk of collision is smaller if the value of *TCPA* is bigger and vice versa. *TCPA* has relations with encountering situation and distance between two ships and relative speed of a target. Until now, there is still no authoritative and uniform approach for appraising the value of collision risk. In section 2.3, some approaches for appraising the value of collision risk will be discussed.

In COLREGS Rule 7, in determining if risk of collision exists the following considerations shall be taken into account:

(1) Such risk shall be deemed to exist if the compass bearing of an approaching ship does not appreciably change;

(2) Such risk may sometimes exist even when an appreciable bearing change is evident, particularly when approaching a very large ship or a tow or when approaching a ship at close range.

2.1.6 Criterions for Appraising Avoiding Actions

According to the past experience and lessons, 4 criterions can be summarized as follows:

'*Early*' criterion means avoiding actions should be positively taken at an early stage. Good seamanship should be considered during the process of implementation of the actions.

'*Substantial*' criterion means avoiding actions should be large enough to be readily apparent to another ship observing visually or by radar; a succession of small alterations of course and/or speed should be avoided.

'*Broad*' criterion means avoiding actions should ensure own ship can pass another ship at a safe passing distance.

'*Clear*' criterion means that when a target-ship has passed at a safe distance, the situation between own ship and it should be monitored so as to ensure own ship will not form new collision risk with it if she plans to return to original course and route.

2.2 Process of Collision Avoidance

2.2.1 Flow Chart of Collision Avoidance

Underway ships should keep proper look-out and safe speed so as to make appropriate judgment in time and take proper avoiding actions early to prevent collisions. The flow chart of the process is show in Fig.2-1:

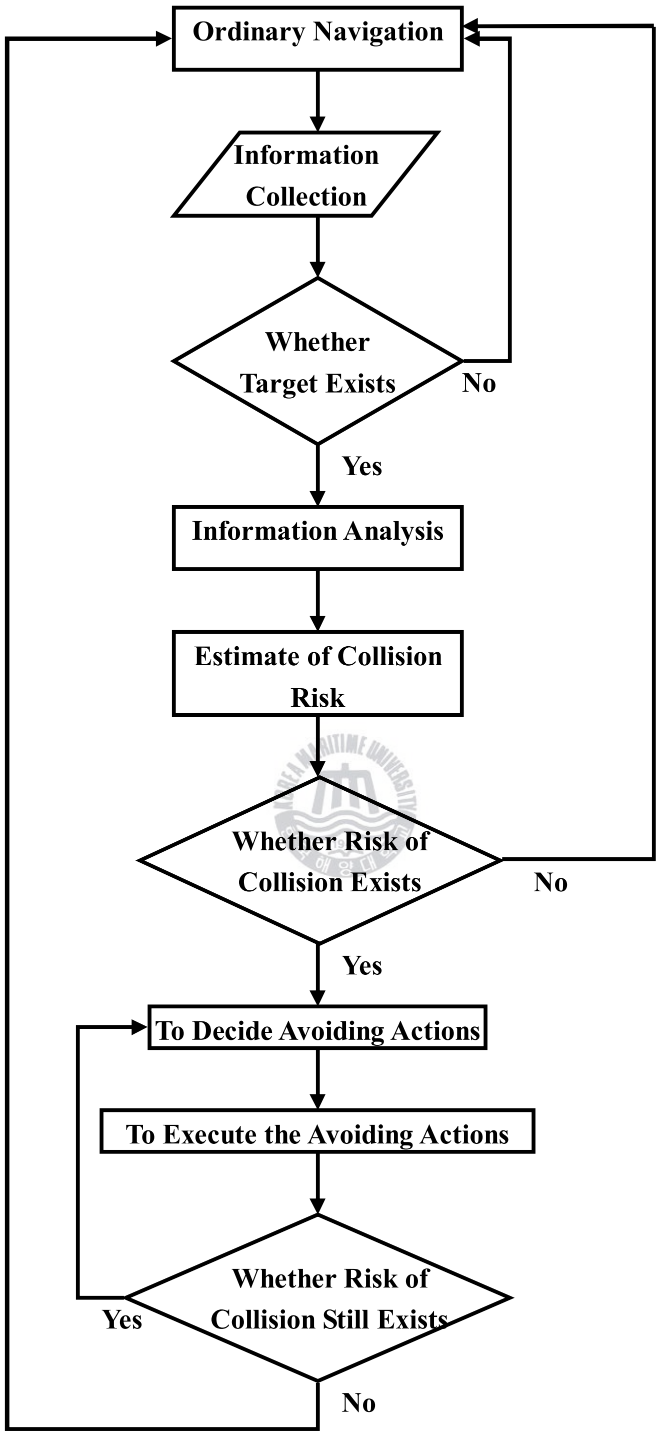


Fig.2-1 Flow Chart of Collision Avoidance

Several steps in Fig.2-1 are explained as follows:

(1) Information Collections

Avoiding actions should be determined based on the information collected from detected targets and navigation environment. And this step is to collect such information by using hearing, sight, radar, AIS receiver, various sensors and so on. Other information collected from waterway books, sea charts and onshore notifications is also important for reference.

(2) Target Detecting

This step is to detect whether targets exist in the vicinity of own ship. If no target exists, own ship should keep ordinary navigation. Otherwise, own ship should analyze the navigational information of the detected targets.

(3) Information Analysis

This step is to prepare the information for appraising collision risk and for making decisions of collision avoidance. For example, using relative movement of a target, *DCPA* and *TCPA* of it can be calculated. Other information such as true movement, navigable area and movement trend of it can be calculated in this step. Moreover, use of AIS makes that necessary data can be prepared more quickly and accurately.

(4) Appraisal of Collision Risk

This step is to use the prepared data to appraise risk of collision between own ship and targets. This step should run through the process of collision avoidance even after avoiding actions are implemented. Ordinary approach for appraising collision risk is to use *DCPA*, *TCPA* and relative bearing of targets. Such approach lies on experience and knowledge of navigators. Usually, navigators set thresholds of *DCPA* and *TCPA* for monitoring the collision risk. If the values are bigger than the thresholds, no risk exists. Otherwise, risk exists.

(5) Determining Avoiding Actions

This step is to determine proper avoiding actions for preventing own ship from colliding with other ships. The determined actions should be able to reduce the collision risk and be readily apparent to other ships observing visually or by radar. Also they should conform to COLREGS and other habits of navigation. Usually, avoiding actions contain alteration of course and alteration of speed. Proper actions should be determined according to the prevailing circumstances and conditions.

(6) Execution and Confirmation of Avoiding Actions

Avoiding actions should be executed correctly. And the effectiveness of the actions should be carefully checked until the other ship is finally past and clear. If other ship takes actions after own ship finishes the avoiding action, the process in Fig.1 should be implemented again until no risk of collision exists.

2.2.2 Safe Passing Distance

Safe passing distance has relations with many factors such as traffic situation, width of navigable water, visibility, weather, size and maneuverability of ship and so on. But according to COLREGS and expertise of navigation experts, safe passing distance should be long enough for preventing ships from forming close-quarters situation. If the encountering situation is not overtaking/overtaken situation, safe passing distance is two(2) nautical miles is considered to be sufficient. And if it is overtaking/overtaken situation, it is one(1) nautical mile is considered to be sufficient because relative speed of the target is not high.

2.2.3 Division of Encountering Process

When the compass bearing of an approaching ship to another ship does not appreciably change, according to Rule 16 and Rule 17 of COLREGS and the relative positions of the two ships, encountering process of them can be divided into four (4) phases. According to the distance between them, the phases are defined as follows: (I) Phase of Effect-free Action; (II) Phase of Involving Collision Risk; (III) Phase of Involving Close-quarters Situation; (IV) Phase of Involving Danger of Collision [37]. And the phases are shown in Fig.2-2.

The range of each phase is not fixed, and it is determined by course angle between two ships, relative speed, maneuverability, traffic density, weather, sea conditions, limitations of water areas and so on. The range of each phase given in

Fig.2-2 is just for reference.

(Phase I) Phase of Effect-free Action

When two ships approach each other from afar and before they become involved in risk of collision, this situation is not regulated in COLREGS. That is to say, ships in this phase are not restricted by COLREGS, and they can take action free. According to the statistics of navigators' behaviors of collision avoidance, only few of them take avoiding actions and most of them do not take any avoiding action in this phase. Distance between two ships is more than 6 nm can be considered as the reference boundary of this phase.

(Phase II) Phase of Involving Risk of Collision

When two ships approach each other so as to involve collision risk, COLREG regulates the give-way ship should, so far as possible, take early and substantial action to keep well clear.

Meanwhile, the stand-on ship should keep her course and speed, take proper observation to the give-way ship and pay attention to change of the current situation. If the stand-on ship collides with other ship because it fails to keep her course and speed, she should be blamed because she does not conform to COLREGS. Statistically, most give-way ships can take substantial actions. But some give-way ships still fail to take proper action for a variety of reasons and should be blamed for causing worse situations. The boundary between Phase I and Phase II is whether two ships become involved in risk of collision. And 3~6 nm can be considered as the reference distance range of this phase.

(Phase III) Phase of Involving Close-quarters Situation

When the two ships continue to approach and the distance between them is less than 3 miles, avoiding action of the give-way ship should be substantial. And the purpose of the action is to prevent them from forming close-quarters situation so as to ensure the two ships can pass at a safe passing distance. If the action of give-way ship does not take appropriate action in compliance with COLREGS, the stand-on ship can give warning sound signals (five short blasts) and warning light signals (five short flashes), and she also may take proper avoiding manoeuvres alone and give manoeuvring sound and light signals. The boundary between Phase II and Phase III is whether two ships become involved in close-quarters situation. And 2~3 nm can be considered as the reference distance range of this phase.

(Phase IV) Phase of Involving Danger of Collision

When distance between the two ships is less then 2 miles, it seems that in close-quarters situation two ships do not take proper avoiding actions in time so that the collision hardly to be prevented and they become involved in danger of collision. In this phase, collision cannot be avoided by the action of the give-way ship alone, and the stand-on ship should also take such action as will best aid to avoid collision. And in order to avoid the immediate danger or reduce the loss of collision, both of the two ships should take the most effective action to avoid each other and even may take the actions departure from COLREGS. The boundary

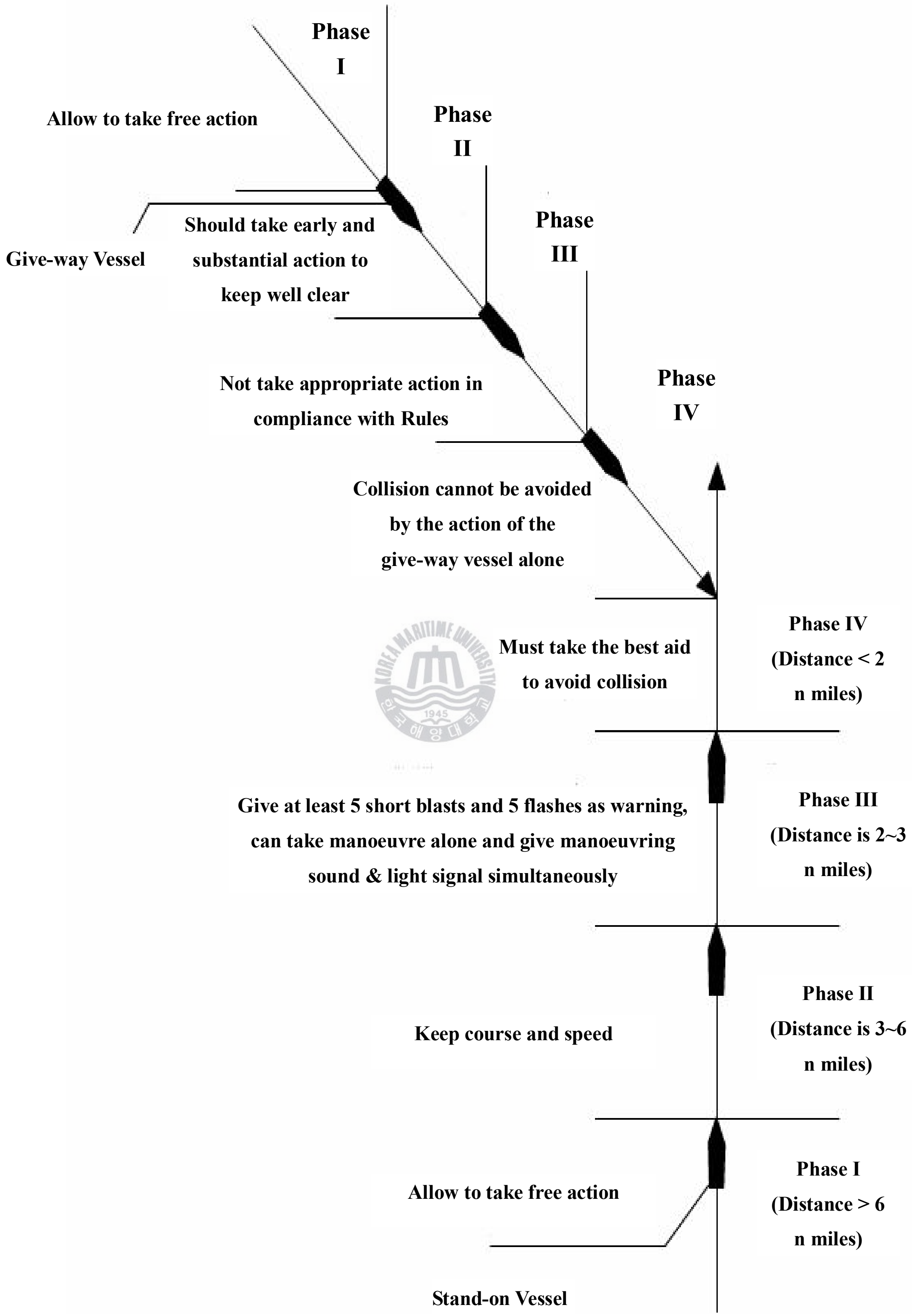


Fig.2-2 Phases of Encountering Process of Two Ships

between Phase III and Phase IV is whether two ships become involved in danger of collision. And less than 2 miles can be considered as the reference distance range of this phase.

2.2.4 Division of Encountering Situations of Ships in Sight of One Another

According to requirements of COLREGS and experience of navigators, a picture of manoeuvring principles is shown in Fig.2-3. In Fig.2-3, own ship locates at the origin and heading of her is 000º. There are 6 sectors in Fig.2-3. When a target approaches from each of these sectors, own ship should manoeuvre as follows:

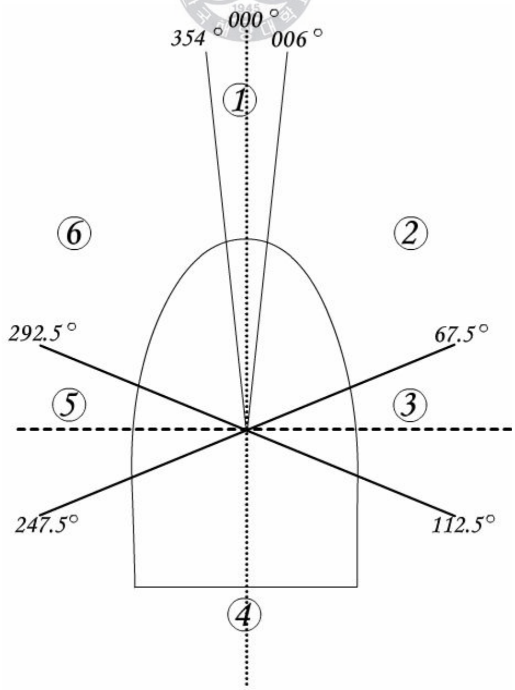


Fig.2-3 Divisions of Collision Avoidance Principles

(1) When a target approaches from Sector ① (354º~360º&000º~006º), if it and own ship are meeting on reciprocal or nearly reciprocal course so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(2) When a target approaches from Sector ② (006º~67.5º), if it and own ship are crossing so as to involve risk of collision, own ship is the give-way ship and the target is the stand-on ship. Own ship should alter her course to starboard substantially and pass astern of the target.

(3) When a target approaches from Sector ③ (67.5º ~112.5º), if it and own ship are crossing so as to involve risk of collision, own ship is the give-way ship and the target is the stand-on ship. In this situation, according to practical navigation experience, the effect of alteration of course to port is obviously better than to starboard. That is because when the bearing of the target is near the beam of own ship, if own ship alter her course to starboard, the relative speed may increase. And this is not favorable for reducing the risk of collision. So own ship should alter her course to port and wait to pass astern of the target.

(4) When a target approaches from Sector ④ (112.5º ~247.5º), if it overtakes own ship, and then it is the give-way ship. But when it does not take proper avoiding action so as to involve risk of collision, own ship should take such action as will best aid to avoid collision. For example, if own ship is overtaken by a target from starboard and forms close-quarters situation with it, she should alter her course to port to avoid.

(5) When a target approaches form Sector ⑤ (247.5º ~292.5º), if it and own

ship are crossing so as to involve risk of collision, own ship is the stand-on ship and the target is the give-way ship. Usually own ship should just keep her course and speed. But when close-quarters situation is formed, own ship should turn to starboard until the target astern.

(6) When a target approaches form Sector ⑥ (292.5º ~354º), if it and own ship are crossing so as to involve risk of collision, own ship is the stand-on ship and the target is the give-way ship. Usually own ship should just keep her course and speed. But when close-quarters situation is formed, own ship should turn to starboard until the target abeam to port.

According to the above manoeuvring principles and related navigation knowledge, the encountering situations between two ships in sight of one another can be divided as shown in Fig.2-4. In Fig2-4, different possible encountering situations are listed. In order to deal with each of the situations, own ship should take appropriate action.

2.2.5 Avoiding Actions of Ships not in Sight of One Another Because of Restricted Visibility

In restricted visibility conditions, if two ships are in sight of one another and close-quarters situation is not formed, avoiding action should conform to the manoeuvring principles in section 2.2.4. And if two ships are in sight of one another and close-quarters situation is formed, it seems to be a special situation that both of the two ships should take proper actions for avoiding collision.

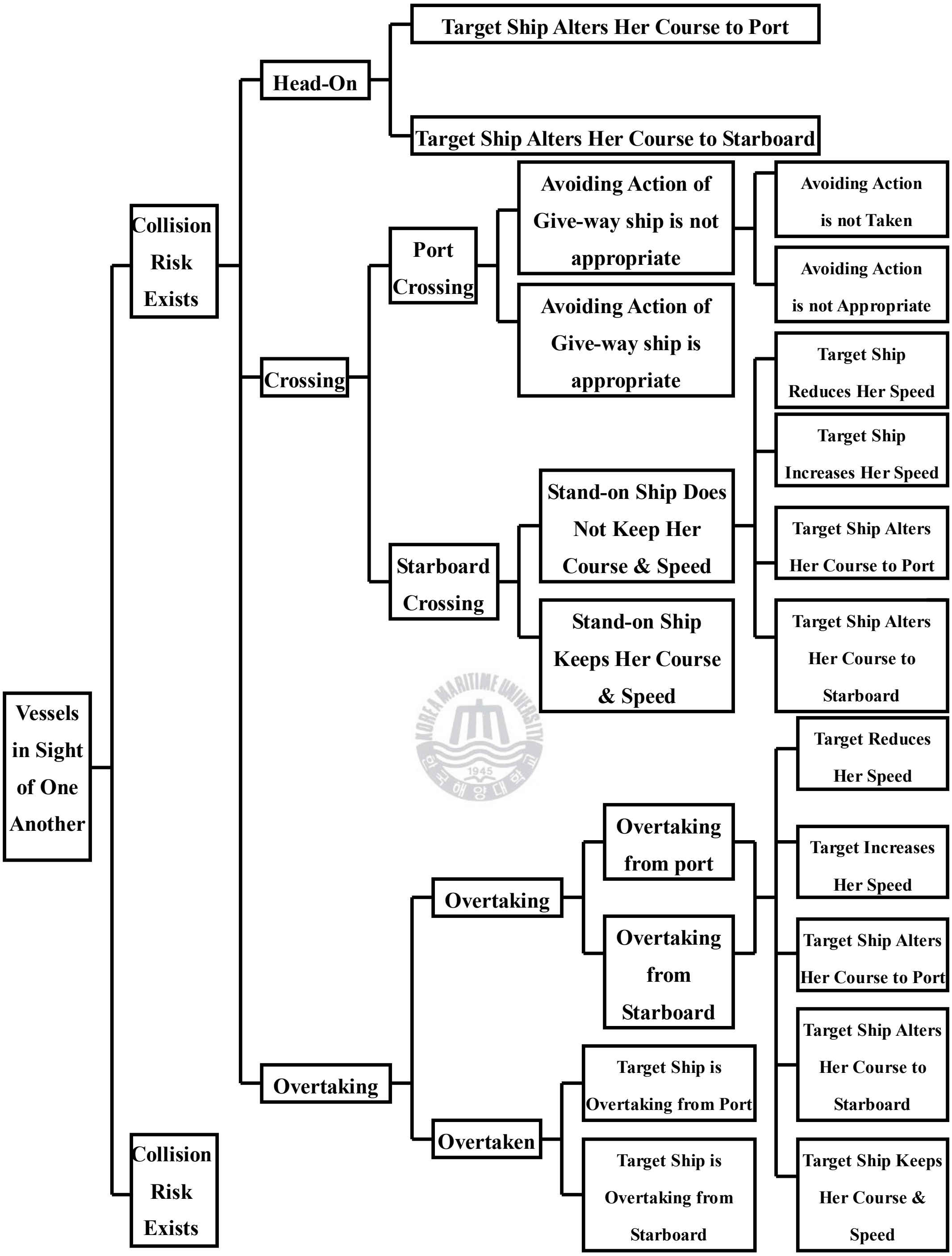


Fig.2-4 Divisions of Encountering Situations of Ships

In restricted visibility conditions, if two ships are not in sight of one another, whatever the situation is formed by the two ships, both of them have the same responsibility for avoiding collision. The principals in section 2.2.4 and divisions of encountering situations are no longer available in this situation.

2.2.5.1 A Target Detected Only By Radar

In this situation, own ship should judge whether close-quarters situation is formed and whether collision risk exists. If collision risk exists, own ship should take avoiding actions at an early stage.

(1) Alteration of Course

In wide water areas, alteration of course is the most effective action for collision avoidance. This kind of action is easy, effective, independent of engine, and can be implemented in short time. So it is the most common action for collision avoidance.

(a) Targets Forward of the Beam

Own ship should avoid to take an alteration of course to port for a ship forward of the beam, other than for a ship being overtaken. So wherever the target is forward of the right beam or the left beam, own ship should alter her course to starboard [48]. The specific situations are shown in Fig.2-5.

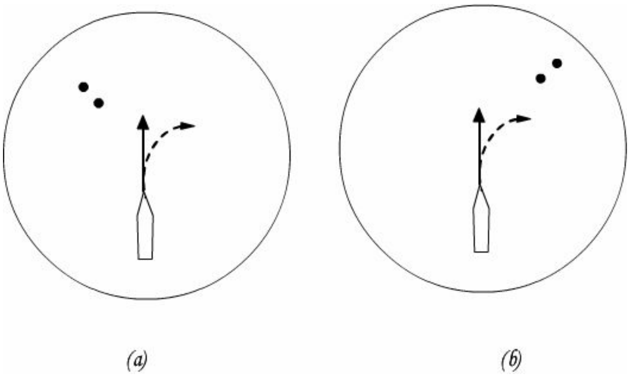


Fig.2-5 Avoid Target Forward of the Beam

(b) Targets Abeam or Abaft the Beam

If own ship alter her course towards a target abeam or abaft the beam, the relative speed will increase so as to cause worse situation. So an alteration of course towards a ship abeam or abaft the beam should be avoided. That is to say, own ship should alter her course towards port when target abeam or abaft the right abeam, and should alter her course towards starboard when target abeam or abaft the left abeam. The specific situations are shown in Fig.2-6.

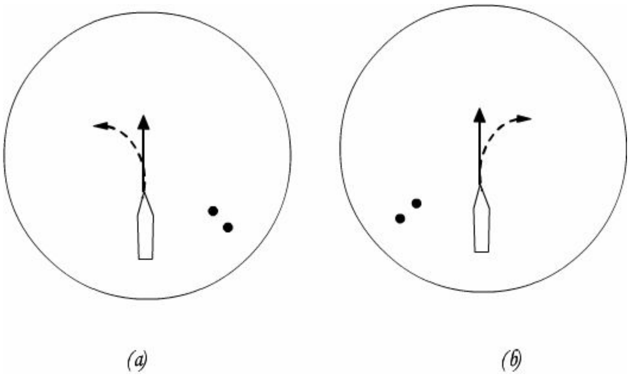


Fig.2-6 Avoid Target Abeam or Abaft the Beam

(2) Alteration of Speed

In some situations, if alteration of course is not available, own ship should reduce her speed to avoid collisions. But the effect of alteration of speed is not apparent and hard to be observed visually or by radar. Therefore, this action should be substantially taken at an early stage if it is determined to be taken.

2.2.5.2 Danger Showed by Fog Signals

Every ship which hears apparently forward of her beam the fog signal of another ship, or which cannot avoid a close-quarters situation with another ship forward of her beam, shall do the following actions:

(1) Reduce her speed to the minimum at which she can be kept on her course.

If own ship cannot avoid a close-quarters situation with another ship of her beam, a blind alteration of course will cause worse situation. So a cautious action is to reduce her speed to the minimum so as to have more time to judge the situation and take emergency avoiding actions.

(2) Take all her way off.

If a fog signal is suddenly heard, or it comes from the beam, or course of a target can not be judgment because of fog, or own ship doubts the actions of other ships, own ship may take her way off by stopping or reversing her means of propulsion so as to have more time to judge the situation.

2.2.6 Divisions of Avoiding Actions

Ordinarily, avoiding actions contain three types such as alteration of course, alteration of speed and alteration of course & speed.

Alteration of course contains alteration of course to port and alteration of course to starboard. Alteration of speed contains increase of speed and decrease of speed. Alteration of speed is commonly used in fog weather and needs the engine to be standby. In some emergencies, alteration of course and alteration of speed will be used simultaneously. Usually, alteration of course is used mostly because it is easy, effective, independent of engine, and can be taken in short time.

In some situations, for example own ship navigates in a narrow area or some other ship is on the path of avoiding action, alteration of course is not available. In such situations, decrease of speed should be considered. And in fog weather, if own ship doubts bearing of a target, she should reduce her speed or take all her way off.

Considering avoiding the target astern, own ship may increase her speed. Sometime, it is an effective avoiding action. But as ships infrequently proceeded at a lower speed than would be considered safe for the prevailing circumstances an increase in speed large enough to satisfy the requirements of Rule 8(b) of COLREGS would usually be in contravention of Rule 6 of COLREGS. So increase of speed is rarely used.

2.3 Value of Collision Risk

In previous section 2.1.5, the description of collision risk has been discussed. Simply speaking, the collision risk is the colliding possibility during the encountering process of ships. And value of collision risk is a number or extent to describe the possibility.

It is a very important job to judge whether own ship becomes involved in collision risk with targets during navigation. So algorithm for appraising collision risk is a key component of an expert system for collision avoidance and it is the important condition of decision-making of collision avoidance. In order to develop an automatic decision-making system for collision avoidance, a mathematic approach for calculating value of collision risk should be determined properly. The approach should be able to properly reveal actual avoiding actions taken by ships. Quantification of the value of collision risk plays an important role in developing an expert system for collision avoidance, especially in the respect of determining the primary ship to avoid.

2.3.1 Approaches for Appraising Collision Risk

In the field of appraising collision risk, in many countries, many studies have been carried out and many theories have been put forward. Generally speaking, these studies are developed through 4 stages as follows:

(1) Theory of Traffic Flow.

This theory is based on frequency of encounters of ships (or times of encounters), previous collision accidents in specific areas and so on to appraise collision risk.

(2) Theories from Microcosmic View.

They are based on human behavioristics and psychology and appraise collision risk by using ship domain and dynamic boundary. Representative scholars are Fujii from Japan and Goodwin, C.M. from Britain.

(3) Theories of Using *TCPA* and *DCPA*.

Nagaawa and Davis think that the effects of *DCPA* and *TCPA* should be considered together for appraising collision risk. But synthetical researches of *DCPA* and *TCPA* are not found in these studies.

(4) Theories of Synthetically Using *TCPA* and *DCPA*.

Iwazaki and Hasegawa set coefficients to *TCPA* and *DCPA*, and then utilize mathematic theories to synthetically use *TCPA* and *DCPA*. But this approach still does not consider other factors well other than *TCPA* and *DCPA*. And it is difficult to use the approach because it is very complicated.

In addition to *TCPA* and *DCPA*, distance from a target, approaching speed, respective bearing, bearing, aspect of a target and so on should also be considered for appraising collision risk. In ESCAN, a new approach is used. It utilizes properties of *sech* function and synthetically considers the factors other than *TCPA* and *DCPA*. It is simple and easy to be used. Before it is introduced, some other approaches will be discussed first to find out the specialties and deficiencies of them.

2.3.1.1 Approach of Simply Using *DCPA* and *TCPA*

For example, a system defines 'if $DCPA \leq 0.5$ nm, danger of collision exists; if $0.5 < DCPA \leq 2.0$ nm, distance between two ships is not ample for passing safely; if $TCPA \leq 7.5$ min, time is not ample for avoiding collision'. Tsuruta from Japan puts forward a five-level theory for appraising collision risk which is based on different values of *DCPA* and *TCPA* [16]. And it is shown in Fig.2-7.

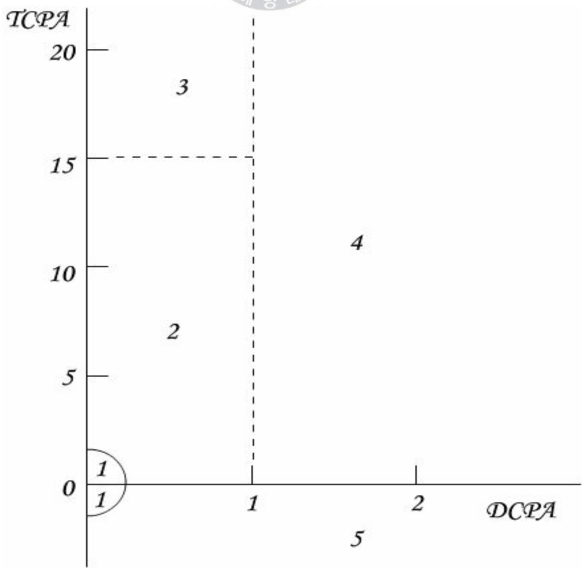


Fig.2-7 Five-Level Theory for Appraising Collision Risk

Kearon and Imazu. et al put forward a model considering *DCPA* and *TCPA* as follows:

$$\rho_i = (a \bullet DCPA_i)^2 + (b \bullet TCPA_i)^2 (i = 1, 2, \cdots, n)$$

Here a and b are weight coefficients according to statistic data, value of ρ is smaller, approaching ship is more dangerous.

But this approach has some problems:

(1) The relationship between appraising value and difficulty of collision avoidance is not explicit.

(2) *DCPA* and *TCPA* of a single target are used in it. It is difficult to be used for appraising multi-target situations.

2.3.1.2 Approach Based on *PAD* (Predicted Area of Danger)

PAD approach uses safe action area to clearly display collision risk. *PAD* is the predicted area of colliding with a target caused by actions of own ship. So collision risk will be reduced if selected course is not in the *PAD* or is in the direction far from it. It is easy to acquire the safe action zone of course by using the approach. If own ship approaches the *PAD*, that is to say, the horizontal width of it becomes bigger, the collision risk becomes higher.

This approach has some deficiencies:

(1) It describes collision risk by using figure of *PAD*. It is hard to acquire numeric values of collision avoidance by using this approach.

(2)Distance from the *PAD* and horizontal width of it have relations with the difficulty of collision avoidance. The difficulty can be judged by using the distribution of *PAD* and the distance from it. But in multi-target situations, such judgments are hard to be made.

2.3.1.3 Approach Based on Course Zone of Colliding and Speed Zone of Colliding

Course of colliding is the course zone of probably colliding with other targets when own ship keeps speed and takes arbitrary alteration of course. And speed zone of colliding is the zone of probably colliding with other targets when own ship keeps course and takes arbitrary alteration of speed. The approach contains current and predicted course or speed of own ship. The zones are bigger, the collision risk becomes higher.

This approach has some problems:

(1) If these zones are bigger, the collision risk is higher is a speciality of this approach. But specific values of them may be ignored when they are used.

(2) The zones are based on the premise that own ship keeps course or speed. And it is possible that own ship has actually become involved in danger when she alters both course and speed.

(3) Maneuverability of own ship is not considered in the approach. Especially when a target approaches own ship, Maneuverability of own ship determines the altering value of course or speed. Therefore, it is necessary to consider this factor.

2.3.1.4 Approach Based on *SOD* (Sector of Danger)

This approach is similar to the approach in section 2.3.1.3 and also uses sector of danger to determine the collision risk. But when own ship alters course and speed simultaneously, the sector of danger can also be acquired. That is to say, the approach can reveal all collision possibility in the *SOD*. The *SOD* is wider, the collision risk is higher. Similarly, this approach also uses figure to display the sector of danger like the approach of *PAD*. And it is also excellent on determining safe action sector of own ship.

But it also has some problems:

(1) If one *SOD* locates bow of own ship and another locates stern of her, and if the distances from them to own ship are equal, the sizes of the two *SOD* are same. But obviously, own ship is easier to take action to avoid a target astern than one fore. So difficulty of collision avoidance can not be expressed only by size of *SOD*.

(2) The approach does not provide numeric value to express collision risk. So it is hard to judge whether or not avoiding actions should be taken.

2.3.1.5 Approach Based on Collision Probability According to Conjectural Position Error

This approach uses *CPA* of a target calculated by its relative movement to conjecture the conjectural position error of it at that time so as to acquire the collision probability for appraising the collision risk.

First step is to use common method to calculate *CPA* of a target and then calculate its relative movement by using the collected information of it. Second step is to calculate the conjectural position error of the target at *TCPA* later. And this conjectural position error is a *CPA*-centric normal distribution. On the other hand, possible colliding zone of own ship is inside a circle. Own ship is the centre of the circle and minimum safe passing distance is the radius of it. The intersectant area between the normal distribution and the circle is the current predicted collision probability ξ. Obviously, if *CPA* is closer to own ship, ξ is closer to 1.

Collision risk can be expressed by using collision possibility and difficult of avoiding. And difficult of avoiding has inverse proportion relationship with *ta* which is the left approaching time of a target. If value of collision risk with a target is set to be *U* and it has the relationship with ξ and *ta* as follows:

$$U = \frac{\xi}{ta}$$

Here, *ta* = Distance from the target / Approaching speed of the target. Value of *U* is bigger, the collision risk is higher.

But this approach still has some problems as follows:

(1) Even *DCPA* of a target is 0 nm, value of collision risk evidently follows size of danger area set by navigators. So a uniform threshold is difficult to be determined.

(2) It is not practical that all navigators set a fixed danger area for preventing the situation in (1). For example, if the danger area is too big, value of collision risk may still be very big even *DCPA* is 1~2 nm. That is to say, value of collision risk may be very big even collision is probably not going to happen.

(3) After avoiding action is taken, left approaching time may decrease instead of reduction of value of collision risk so that the value of collision risk is bigger than threshold. But in such situation, according to the value of collision risk, even the actual situation may still be safe, navigator also should consider re-avoiding action.

(4) The approach uses collision probability and left approaching time to express collision risk. But some other factors used in actually process of collision avoidance such as relative bearing and aspect of a target are not fully considered in it.

(5) When left approaching time is close to 0, discontinuous situation of value of collision risk will happen. That is to say, value of collision risk may change form maximum to minimum. For this reason, when distance from a target is very close, for example less than 0.1 nm, value of collision risk may be very small. Obviously, this is not fit for our common sense.

2.3.2 Approaches Using Specialities of *Sech* Function for Appraising Collision Risk

2.3.2.1 Approach of Jeong for Appraising Collision Risk

Jeong puts forward a new approach for appraising collision risk by using specialities of *Sech* function [18], [19], [20], [21]. The approach solves the problems mentioned in section 2.3.1.1~2.3.1.5 to some extent. In the approach 'left approaching time' is used, but it is renamed as 'time of approach '(*ta)*, but the meaning of it is not changed.

ta = Distance from the target / Approaching speed of the target

And the new approach is as follows:

$$CR = p.\operatorname{sec}h(a.dcpa) + q.\operatorname{sec}h(b.ta) + r.\phi(\theta,\alpha) \quad (2\text{-}1)$$

Here, *CR* is value of collision risk; *dcpa* is distance to closest point of approach; *ta* is time of approach; *p, q, r* are the amplitude coefficients; *a* and *b* are the coefficients of *sech* function; $\phi(\theta,\alpha)$ is state function of own ship. $\phi(\theta,\alpha)$ is a function for determining whether own ship maintains her course and speed or alters her course and/or speed according to the COLREGS. It is expressed by the bearing θ and the aspect α of a target, the magnitude of which is 0 if own ship is in the stand-on state and 1 if she is in the give-way state.

Jeong discussed the approach in his studies and acquired some satisfied results.

2.3.2.2 New Modification Approach

In order to acquire better effect of appraising collision risk, a new modification approach is proposed and researched in this paper. And the approach is as follows:

$$CR = \frac{p.\operatorname{sec}h(a.dcpa)}{ta} + r.\phi(\theta,\alpha) \quad (2\text{-}2)$$

The meanings of coefficients in formula (2-2) are similar to those in formula (2-1). That is to say, *CR* is value of collision risk; *dcpa* is distance of closest point of approach; *ta* is time of approach; *p, r* are the amplitude coefficients; *a* is the coefficient of *sech* function; $\phi(\theta,\alpha)$ is state function of own ship and is expressed by the bearing θ and the aspect α of a target, the magnitude of which is 0 if own ship is in the stand-on state and 1 if she is in the give-way state [22].

2.3.2.3 Some Reasons for Modification

(1) When *DCPA* decreases *CR* will increase. Generally the decrease of *DCPA* means that the risk of collision increases. In addition if *DCPA* is equal or nearly equal to zero, we regard it as equally dangerous. For example, if *DCPA* is 0 and 0.1 mile respectively, collision risk will be almost the same intuitively. By using sech function, *DCPA*s of 0 and 0.1 miles will be 1 or 0.9950 respectively. In this regard Equation (2-2) can be considered to represent collision risk well by using sech function.

(2) Because in Equation (2-1) *ta* values of different signs are the same ones, it means that even a target, which passed through its *CPA*, has still the same collision risk and it may be absurd. Equation (2-2) is to depict (-) value just after the passing of *CPA* and represents to get out of risk.

2.3.2.4 Some Factors Used in the Modification Approach

(1) *DCPA*

$$\mathrm{DCPA} = R \cdot \sin\zeta \tag{2-3}$$

$$\zeta = \left|C_r - (\theta + 180)\right| \tag{2-4}$$

Here, R is distance from a target; ζ is relative moving angle of a target, and is the angle between the direction of relative movement and the line from own ship to the target. The range of ζ is $0 \le \zeta \le 180$. C_r is course of relative movement of the target. θ is bearing of the target. The relationship of these factors is shown in Fig.2-8.

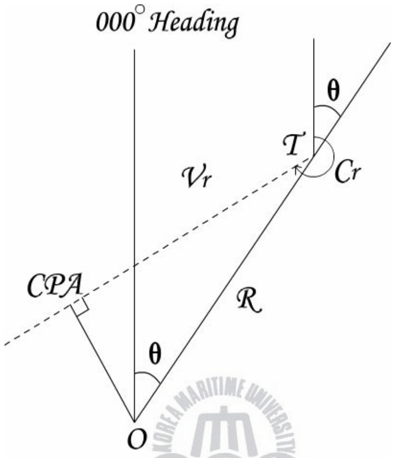


Fig.2-8 Relationship of Navigational Factors

(2) *TCPA*

It is only meaningful when *TCPA* and *DCPA* are used together. That is to say, only small *TCPA* of a target does not definitely lead to collision risk. So by using *TCPA*, it is hard to know approaching remaining time of a target when it approaches own ship. But time of approach *ta* can express this concept well.

(3) Time of Approach *ta*

In order to solve the deficiency mentioned in (2) of this section, time of approach *ta* is used in the modification approach. It can be calculated as follows:

$$ta = \frac{R}{v_r \cos\zeta} \tag{2-5}$$

Here, *ta*(min) is the time of approach and is the remaining approaching time of a target; V_r (nm/h) is relative speed of the target; ζ has the same meaning as is mentioned above in (1) of this section.

(4) Aspect of a Target *α*

Aspect of a target α is the angle from heading of a target to the line of sight of own ship to the target. And it is shown in Fig.2-9. And the formula for calculation α is as follows:

$$\begin{cases} \alpha = \theta - H_T + 180^\circ \\ \alpha = \alpha - 360^\circ, \quad if\ \alpha > 180^\circ \end{cases} \tag{2-6}$$

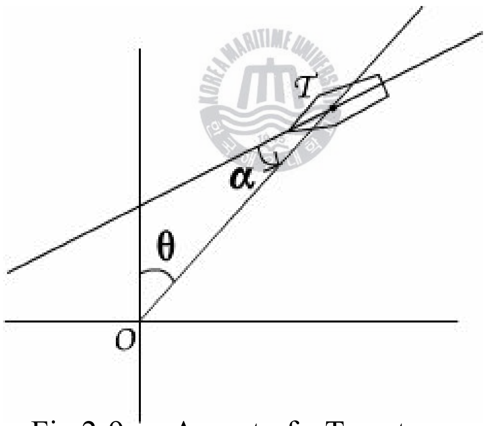


Fig.2-9 Aspect of a Target

Here, θ is bearing of a target; H_T is heading of the target. If drift angles caused by wind, wave and current can be ignored, H_T can be replaced by C_T which is course of the target.

Concerning aspect of a target, some points should be explained as follows:

$\alpha = 0^o$ means the bow of a target is dead against own ship;

$\alpha = 180^o$ means the stern of a target is dead against own ship;

$\alpha = 90^o$ means the starboard beam of a target is dead against own ship;

$\alpha = -90^o$ means the port beam of a target is dead towards own ship;

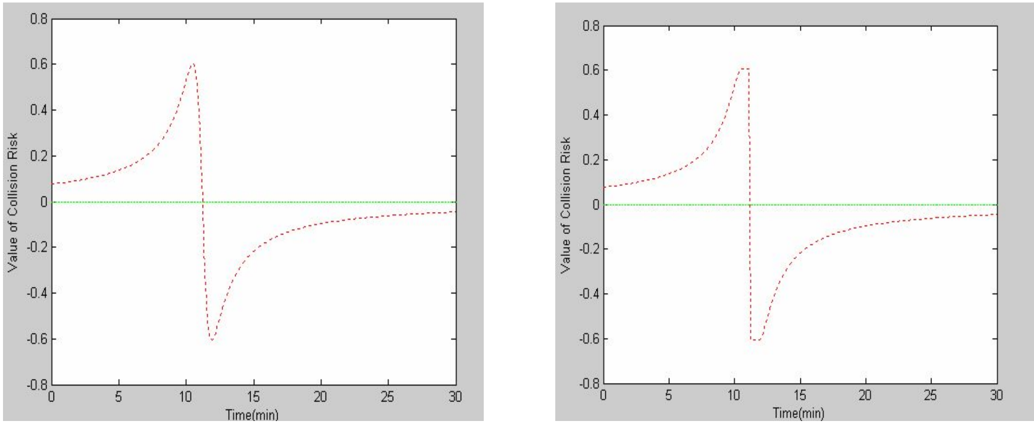
$\alpha > 0^o$ is called starboard aspect of a target and means starboard of the target is towards own ship;

$\alpha < 0^o$ is called port aspect of a target and means port of the target is towards own ship.

2.3.2.5 Modification of *ta*

In Equation (2-2), $ta = 0$ is a discontinuity point. When ta is 0, CR will be discontiguous. But only when collision really happens, value of ta is 0. So in ordinary situations, this point can be ignored.

When a target approaches own ship and both of the two ships keep their speed and course, value of collision risk calculated by the modification approach can be acquired and shown in Fig.2-10(a). In Fig.2-10(a), value of collision risk increases to maximum before the target passes *CPA* and then it drops sharply to zero until the target passes *CPA*. That is to say, when the target is very close to own ship, for example, the distance is within 0.1 mile, the *CR* will be so slow. Of course, this situation is not fit for intuitionistic observation. Maximum of *CR* should appear at the moment just before the target passes *CPA* and then sign of *CR* changes from plus to minus.



(a) Value of *CR* without modification of *ta* (b) Value of *CR* with modification of *ta*

Fig.2-10 Value of *CR*

Based on formula (2-3)~(2-5), a formula for calculating *ta* can be acquired as follows:

$$ta = \frac{2DCPA}{V_r \sin 2\xi} \tag{2-7}$$

According to formula (2-7), *ta* reaches extremums if ξ is 45ºor 135º. According to the expertise of navigation, when a target approaches own ship and passes CPA, value of ξ changes quickly. That is to say, it will change from 45º to 90º in very short time. If 45º<ξ<90º, target is comparatively close to own ship. And if ξ keeps increasing, obviously *CR* does not have trend to decrease, but value of *ta* increases very quickly. And this leads to sharp decrease of CR. But this obviously does not fit for actual situation and common sense. So when $\xi \in$(45º，90º) and $\xi \in$(90º，135º), values of *ta* should be modified. And in the approach, when $\xi \in$(45º，90º) values of *ta* are set to the value of *ta* when ξ is 45º. and when $\xi \in$(90º，135º) values of *ta* are set to the value when ξ is 135º. And considering the situation when target passes

CPA, ξ is 90º, so the approaching speed of the target to own ship is 0. That is to say, *CR* is 0. And the modification formula of *ta* is shown as follows:

$$ta = \left. \begin{array}{ll} \dfrac{2DCPA}{V_r} & if \quad 45^\circ < \xi < 90^\circ \\ = -\dfrac{2DCPA}{V_r} & if \quad 90^\circ < \xi < 135^\circ \\ = \infty & \xi = 90^\circ \\ = \dfrac{R}{V_r \cos\xi} & otherwise \end{array} \right\} \qquad (2\text{-}8)$$

And under the same condition of Fig.2-10(a), the value of collision risk using formula (2-2) and (2-8) can be acquired and shown in Fig.2-10(b).

2.3.2.6 Determining Coefficient *a*

For determining coefficient '*a*' simply, the amplitude coefficients of modification approach are supposed as *p* is 1 and *r* is 0.

Commonly, when a target approaches own ship, target's *CR* value's difference between *CR* values before and after action is a criterion to judge whether the action is effective or not. If the difference is minus, that is to say after-action *CR* is bigger than before-action. And it is to say the action is not effective and should be adjusted. Obviously, if the difference can get to its maximum, the action taken is most effective one. Here, the difference can be defined as follows:

$$F = CR_1 - CR_2 = \frac{\sec h(a.dcpa_1)}{ta_1} - \frac{\sec h(a.dcpa_2)}{ta_2} \qquad (2\text{-}9)$$

Here, $dcpa_1$ and ta_1 mean target's values of approaching time before action taken, and $dcpa_2$ and ta_2 are the values when the approach time reaches its maximum after avoiding action taken. The result of F in (2-9) should be bigger than 0.

When $dcpa_1$,$dcpa_2$,ta_1 ,ta_2 are all known, F is a function of 'a' as equation (2-10).

$$F(a) = \frac{\sec h(a.dcpa_1)}{ta_1} - \frac{\sec h(a.dcpa_2)}{ta_2} \tag{2-10}$$

When the derivative of $F(a)$ is 0, the value of 'a' can be obtained and the maximum of $F(a)$ can be acquired.

$$\begin{aligned}\frac{dF}{da} &= \frac{-\sec h(a \cdot dcpa_1)\tanh(a \cdot dcpa_1)}{ta_1} dcpa_1 \\ &+ \frac{\sec h(a \cdot dcpa_2)\tanh(a \cdot dcpa_2)}{ta_2} dcpa_2 \\ &= 0\end{aligned} \tag{2-11}$$

The value of 'a' obtained from (2-11) is that when the value of dF/da is 0, and $dcpa_1 < dcpa_2$, then $F(a)$ can reaches its maximum. The bigger $F(a)$'s value is, the better the effect of the avoiding action is.

2.3.2.7 Flow Chart of obtaining Coefficient *a*

The method to get the value of coefficient a is shown in Fig.2-11. There are two points should be explained:

(1) The value of coefficient a should be such that the value of F is bigger than 0. Otherwise, ta_2 should be calculated and adjusted again. If the value of a is such that F is not bigger than0, target's CR, will not be decreased only by the avoiding action taken. So some other avoiding actions should be taken. This process will

continue until *F* is bigger than 0.

(2) Usually, $ta_2<ta_1$.Only when the vessel's speed is very low, $ta_2>ta_1$ could happen. But this situation almost has no effects to $F>0$.

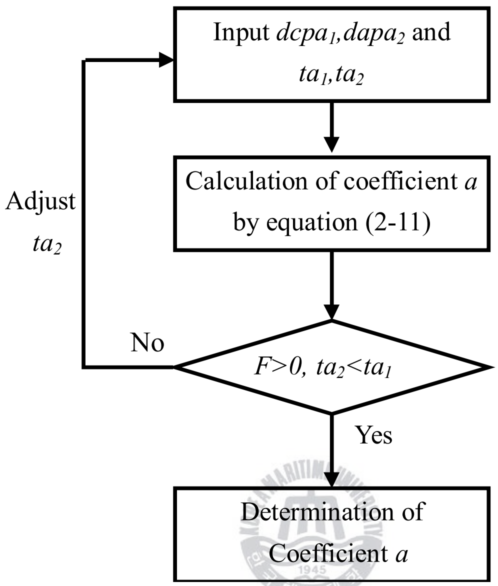


Fig.2-11 Procedure of Getting Coefficient *a*

2.3.2.8 The Meaning of Getting Value of Coefficient *a*

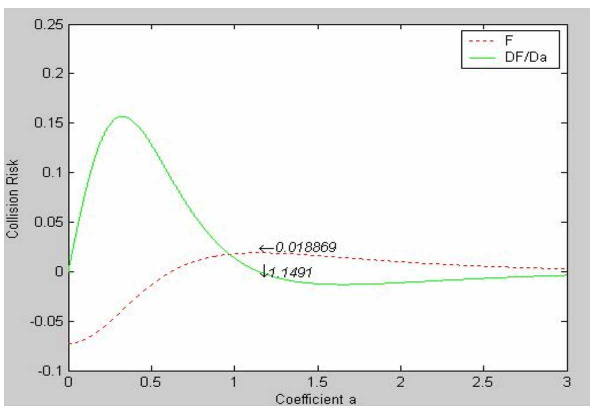


Fig. 2-12 Collision Risk Difference *F* by Coefficient *a*

The meaning of the formula (2-11) is shown in Fig.12. In Fig.12, for obtaining coefficient *a*, we assume that $dcpa_1$ is 1.5 miles and $dcpa_2$ is 2.3 miles, ta_1 is 6.998 minutes and ta_2 is 4.635 minutes. Substituting these into formula (2-10) and formula (2-11), the graphics of *F* and *dF/da* can be taken in Fig.8. In Fig.8, at the point where *dF/da* is 0, the value of *a* is 1.1491. And at this point, $F(\xi)$ = 0.018869 is the maximum. So the value of coefficient *a* is determined to be 1.1491.

2.3.2.9 Validation of Coefficient *a*

In order to verify the coefficient *a*, some examples are given. Here before-action *dcpa* is 1.5 miles and *dcpa* after the avoidance action is expected to be at least 2.3 miles. And the *CR* maximum after the avoidance action will be considered as collision risk.

Own ship's initial course is 000º and the target's initial course is 180º. Assume that the relative speed is 1.0(mile/min) the speeds of own ship and the target are 0.5(mile/min) respectively. And the target's initial position is 9.0 miles and its bearing is 000º. When the approach time is 7.0 minutes, the avoidance action will be taken. The result will be reasonable.

The relative speed is 0.1(mile/min) the speed of own ship and the target is 0.05(mile/min) the speed of own ship and the target is 0.05(mile/min) respectively. The target initial position is 5.0 miles and bearing is 000º. If the avoidance action is taken when the approach time is 7.0 minutes, the target is too close to own ship, it is not appropriate. So the avoidance action should be taken when the range is 3.25

miles.

The avoidance action of own ship is supposed to change course from 000º to 035º in the two situations. And the value of coefficient *a* is 1.1491.

Fig.2-13 shows the *CR* of relative speed of 1.0(miles/min) with, the before-action *dcpa* of 1.5 mile. When the approach time is 7.0 minutes (i.e. approach distance is 7.0 miles) and own ship changes its course, the *dcpa* will be 2.3 miles. And the before-action *CR* is 0.0494, and it is bigger than 0.0435 which is the maximum value of collision risk after the action.

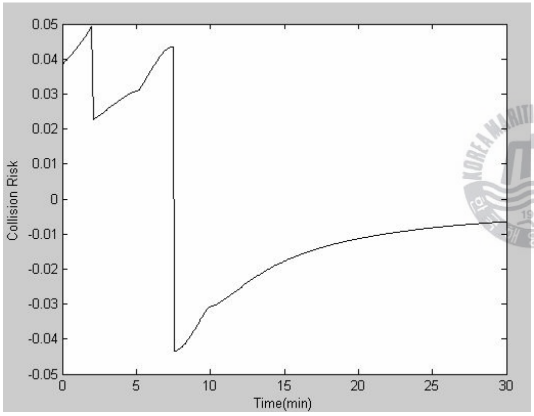


Fig. 2-13 Collision Risk in case of Relative Speed 1.0(mile/min)

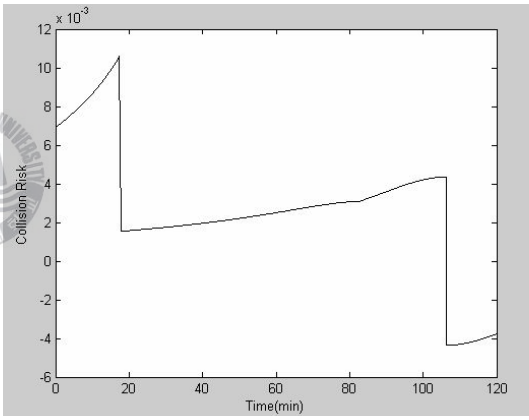


Fig. 2-14 Collision Risk in case of Relative Speed 0.1(mile/min)

Fig.2-14 also shows the *CR* of relative speed of 0.1(mile/min) with the before-action *dcpa* of 1.5 miles. When the approach distance is 3.25 miles and own ship changes its course, the *dcpa* will be 2.3 miles. And the before-action *CR* is 0.010608, and it is bigger than 0.004353 which is the maximum value of collision risk after action.

Another two situations of relative speeds of 0.7 and 0.5 mile/min are also applied to validate coefficient *a*. It appears the same result that the before-action *CR* is bigger than *CR* maximum after action taken.

As a result the value of coefficient *a* is 1.1491 is fit when the CR values are smaller than before-action. If the relative speed is high, the appropriate time to take the avoidance action should be selected when the approach time is 7.0 minutes. And when the relative speed is low the time to take the avoidance action should be selected when the approach distance is 3.25 miles.

So, the formula to calculate value of collision risk is shown as follows:

$$CR = \frac{\sec h(1.1491 * dcpa)}{ta} \tag{2-12}$$

2.4 Multi-target Collision Avoidance

COLREGS provides regulations for defining encountering situations when two ships encounter and regulates the responsibilities and rights of them during the process of collision avoidance. But COLREGS does not provide related rules for dealing with multi-ship situations. According to the explanations of COLREGS, multi-ship situations are special ones and should be dealt with by using good seamanship and related usable regulations in COLREGS. Navigational expertise plays an important role in multi-ship collision avoidance.

Because there are no specific regulations for multi-ship encountering situations in COLREGS, ordinarily, navigators consider the following points for dealing with these situations.

(1) Judging the encountering situations with target-ships.

(2) Predicting the movement trends of target-ships.

(3) Determining the primary target-ship to avoid.

(4) Determining the timing to take avoiding actions.

(5) Considering the safe zone of action.

(6) Considering the typical cases of multi-ship collision avoiding with good seamanship

In order to deal with multi-ship encountering situations in ESCAN, these points should be dealt with well.

2.4.1 Judging Encountering Situations with Target-ships

In multi-ship collision avoidance situations, own ship should judge encountering situations with target-ships. Although COLREGS only regulates encountering situations (head-on, crossing, overtaken and overtaking situations) between two ships, these terms of encountering situations also can be used to describe encountering situations between own ship and targets respectively in multi-ship situations. Based on these judgments of encountering situations, navigators may make proper decision of avoiding action by using the related regulations in COLREGS. But sometime, obligations required by COLREGS are hard to be implemented.

In Fig.2-15, own ship and *target A* are in a port forward crossing situation, and own ship is the stand-on ship according to COLREGS and should keep her course and speed. Meanwhile, own ship and *target B* are in a starboard abaft the beam crossing situation, and own ship is the give-way ship according to COLREGS and should keep out of the way of *target B*. Under this situation, own ship is both the stand-on ship and the give-way ship and can not implement the contrary obligations required by COLREGS.

Judgments of encountering situations are to know better the actual situation of multi-ship collision avoidance situation. If conditions permit and own ship is capable of conforming to COLREGS, own ship must conform to COLREGS. Otherwise, actions with good seamanship or even actions departure from COLREGS may be used to prevent own ship from colliding with other ships. In the situation shown in Fig.2-15, according to COLREGS, own ship should keep course and speed for *Target A* and alter her course towards port substantially for *Target B*. Obviously, the action for *Target B* is against the rule *'not alter course to port for a vessel on her own port side'* because *Target A* is right on her port side. So own ship should slacken her speed or take all way off by stopping or reversing her engine. And this action is proper and cautious for the case.

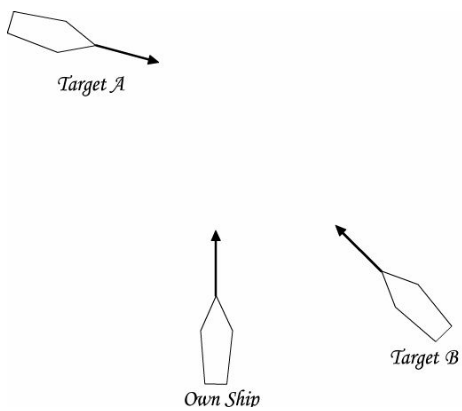


Fig. 2-15 Multi-Targets Collision Avoidance Scene 1

2.4.2 Predicting the Movement Trends of Target-ships

In multi-ship encountering situation, according to the encountering situations between own ship and target-ships judged in 2.4.1, own ship can know the avoiding relationship with each target-ship. Target-ships also have this similar avoiding relationship each other. And they also determine their own decision for collision avoidance according to such relationship. But disharmony of actions may exist in the decisions of own ship and targets so as to cause close-quarters situation. In order to avoid the disharmony, own ship can predict the movement trends of target-ships according to their trajectories and the avoiding relationship of them. And according to the prediction, own ship can know the developing trend of the situation in advance and the possible avoiding actions of target-ships so as to avoid being involved in new collision risk after avoiding action is taken.

It is easy to acquire navigational information of targets in the vicinity of own ship by using AIS. The information contains targets' bearing, speeds, positions and so on. The avoiding relationship among target-ships can be calculated according to the information. Predicting the movement trends of target-ships is to use the ESCAN to make a simplified decision-making for each target-ship. But modification should be made to these predicted decisions of target-ships according to the developing situation. The reason for the modification is that actual actions taken by the targets may not be in accordance with these predicted ones. Once unpredicted actions are detected, system should modify the predicted actions of target-ships according to the new situation. The process of predicting the movement trends of targets is shown in Fig.2-16 as follows:

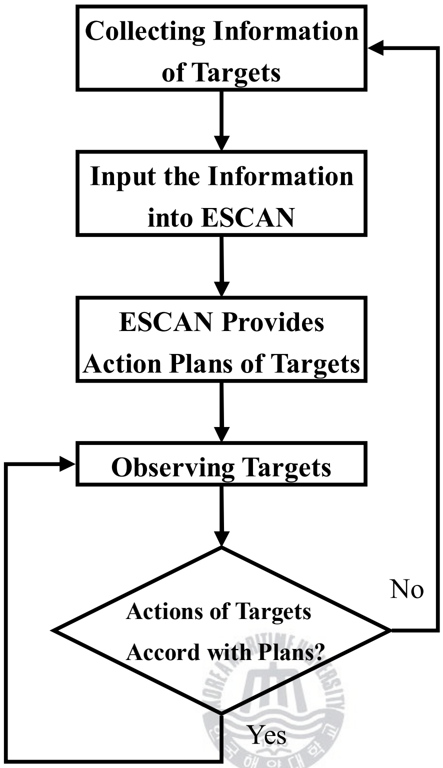


Fig. 2-16 Process of Predicting Movement Trends of Target-ships

As the process shown in Fig.2-16, ESCAN provides the predicted actions of target-ships and modifies them when unpredicted actions are detected so as to provide accurate and timely prediction of movement trends of target-ships for decision-making of collision avoidance of own ship.

2.4.3 Determining the Primary Target-ship to Avoid

During navigation, own ship should try not to be involved in a complicated multi-ship encountering situation. Own ship should collect information of other ships when they approaches own ship from afar, and prevent forming multi-ship encountering situation. But in practical process of collision avoidance, most navigators do not take avoiding actions when distances from other ships are more than 6 nm and do them when the distances are 3~5 nm. So sometimes own ship has to deal with some these complicated situations. In such situations, a common method is to select one target-ship as the primary target-ship to avoid. That is to say, select one target-ship which is most dangerous to own ship as the primary target-ship to avoid.

In multi-ship encountering situation, own ship may meet several ships at the same time and form an encountering situation regulated by COLREGS with each target-ship. Eventually, own ship should select one ship as avoiding target. So no matter how complicated the situation may be, navigators should analyze encountering situation between own ship and each target-ship and make an overall judgment of current situation, and then make a decision for avoiding the most dangerous target. And own ship should keep observing after avoiding actions are taken and avoid current the most dangerous target again if collision risk still exists. And this process continues over and over until own ship passes well clear off all target-ships. The most dangerous target-ship is the primary target-ship to avoid. Usually, value of collision risk is a criterion to select the primary target-ship to avoid. Because value of collision risk has relations with many factors, that of each target-ship should be different. Values of collision risk of different target-ships may be same sometime; however, this is just instantaneous appearance and does not effect the selection of the primary target-ship.

2.4.4 Determining Timing to Take Avoiding Actions

In multi-target encountering situation, decision of collision avoidance should be taken at proper timing. So the timing to take avoiding actions should be determined properly. When own ship is the stand-on ship and is also the give-way ship, own ship has double responsibilities. But actions of the stand-on ship and actions of the give-way ship are contrary. So in this situation, most of navigators choose to take positive avoiding actions. But how to determine the timing to take avoiding actions is still a problem. As the stand-on ship, own ship should keep course and speed. And if own ship does not take avoiding actions at proper timing, other target-ships may misunderstand the purpose of own ship and be involved in collision risk because of the inharmony in the avoiding actions of own ship and other target-ships. Moreover, if the give-way ship does not take avoiding action in time, navigators of the stand-on ship will feel more pressure. So it is very important to determine the timing to take avoiding actions.

If the ships are in sight of one another, COLREGS regulates that the give-way ship should take early and substantial action to keep well clear. For this 'early', navigation experts have some different explanations as follows:

(1) Considering this 'early' is a conception of time, two ships should take action at early time.

(2) Considering this 'early' is a conception of distance, two ships should take action far from each other, and many navigators support this point of view.

(3) Considering this 'early' is a conception relating *DCPA* and *TCPA*, and it

should be grasped by considering time and distance.

In this paper, timing to take avoiding actions is determined by visibility and approaching speed of target-ships. Based on full consideration of the above three points and section 2.2.3 (Division of Encountering Process), regulations for determining the timing to take avoiding actions are as follows:

(1) If ships are in sight of one another, own ship is the give-way ship, and approaching speed of a target-ship is less than 30 knots, own ship should take avoiding action when the distance from the target-ship is 4 nm; and if approaching speed of the target-ship is more than 30 knots, own ship should take avoiding action when approaching time of the target is more than 8 minutes. And this rule does not apply to overtaking situation.

(2) If ships are in restricted visibility, own ship should take avoiding action, and approaching speed of a target-ship is less than 30 knots, own ship should take avoiding action when the distance from the target-ship is 5 nm; and if approaching speed of the target-ship is more than 30 knots, own ship should take avoiding action when approaching time of the target is more than 10 minutes. And this rule does not apply to overtaking situation.

(3) If own ship is the stand-on ship or is overtaking a target-ship, she should take avoiding action when the distance from the target-ship is 2 miles.

(4) If own ship is overtaken by a target-ship and ships are in sight of one another, own ship should take avoiding action when the distance from the overtaking ship is less than 0.7 nm; and if own ship is an overtaken ship and ships are in restricted visibility conditions, own ship should take avoiding action when

the distance from the overtaking ship is less than 1nm.

2.4.5 Considering the Safe Action Zones

As the contents discussed in section 2.3.1.3, course zone of colliding and speed zone of colliding can be calculated for a single target. And the supplementary sets of these colliding zones are safe action zones of own ship. That is to say, when own ship keeps her speed and only takes arbitrary alteration of course for avoiding collision, the zone that own ship can pass a target at a safe distance is the safe action zone of course. Similarly, when own ship keeps her course and only takes arbitrary alteration of speed for avoiding collision, the zone that own ship can pass a target at a safe distance is the safe action zone of speed. Obviously, these zones are determined by value of threshold of collision risk.

In multi-ship encountering situations, if value of threshold of collision risk is set, such zones can also be acquired by calculating the intersection of such zones of each target. These action zones are very important information for navigators to manoeuvre. By using the information, navigators can take avoiding actions with proper magnitude.

Concerning the example in Fig2-17, own ship is involved in a multi-ship encountering situation with two target-ships. *Target A* is dead ahead and *Target B* is on the starboard side of own ship. The safe action zone of course to *Target A* is [109.0° ,251.0°] and such zone to *Target B* is [148.7° ,291.6°]. Therefore, considering the two ships, the safe action zone of own ship is [148.7° ,251.0°].

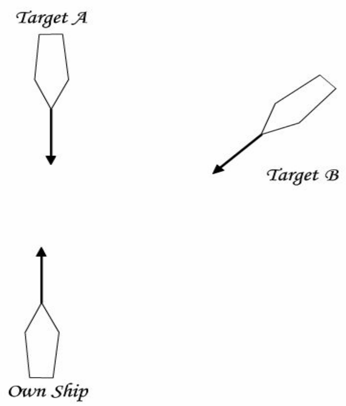


Fig. 2-17 Multi-Targets Collision Avoidance Scene 2

2.4.6 Considering the Typical Cases of Multi-ship Collision Avoidance with Good Seamanship

Because multi-ship encountering situation is complicated, according to COLREGS, proper avoiding decisions are hard to be determined in short time, or alteration of course of the decision is too large, or the decision leads to large deviation from original route, or no decision is available. During practical navigation, in order to avoid these unwanted situations, experienced navigators deal with multi-ship collision avoidance by using good seamanship and some flexible, simple but effective avoiding actions.

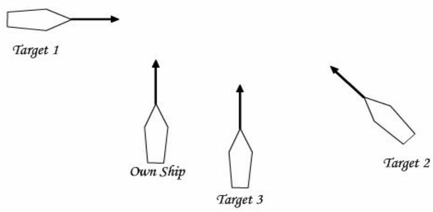


Fig. 2-18 Multi-Targets Collision Avoidance Scene 3

In Fig.2-18, this is a case of multi-ship collision avoidance, and it happens in restricted visibility condition. There are three target-ship in the vicinity of own ship. After analyzing and judging encountering situations between own ship and each target, own ship and *Target 1*are in a port forward crossing situation; own ship and *Target 2* are in a starboard abaft the beam crossing situation; own ship and *Target 3* are in a kind of paralleling situation. According to the value of collision risk of each target, *Target 1* is the most dangerous target to own ship and it should be selected as the primary target-ship to avoid. So this multi-ship encountering situation is a kind of port forward crossing situation. According to COLREGS, own ship should alter her course towards starboard. But obviously, if own ship does so, she will be involved in close-quarters situation with *Target 2*. So this action should be vetoed. And substantial course alteration to port side is also obviously not in accordance with COLREGS because own ship should avoid to alter her course to port for a ship on her own port side. In this situation, experienced navigators choose decrease of speed as the decision of collision avoidance. Own ship should wait for *Target 1* to pass the bow and keeps observing *Target 2* and *Target 3*, and return to original course and route until she passes well clear off the all three target-ships.

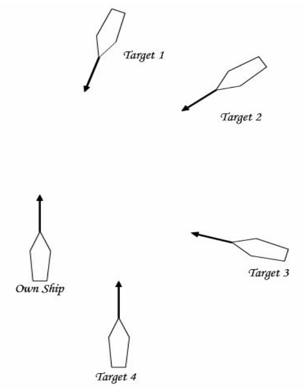


Fig. 2-19 Multi-Targets Collision Avoidance Scene 4

In Fig.2-19, there are four target ships in the vicinity of own ship. And *Target 1* locates forward of the beam of own ship; *Target 2* locates abeam of own ship; *Target 3* locates abaft the beam of own ship; *Target 4* overtakes own ship from the stern of own ship. And the result of analyzing the encountering situations shows *Target 1* is the most dangerous target ship and it is should be selected as the primary target-ship to avoid. According COLREGS, own ship should alter her course towards starboard for avoiding *Target 1*. But if own ship does so, she will become involved in close-quarters situation with *Target 2*. And if own ship takes another alteration of course to starboard for avoiding *Target 2* according to COLREGS, she will continue become involved in danger of collision with *Target 3* or even directly collide with *Target 4*. In this situation, experienced navigators always take substantial alteration of course towards port or substantial decrease of speed for avoiding the possible close-quarters situation and danger of collision. But all the avoiding actions should be taken early for seizing the initiative of collision avoidance.

In order to use the good experience of these typical cases of multi-ship collision avoidance with good seamanship, they are absorbed into ESCAN as a part of knowledge base of it. If current situation is in accordance with a case, the case will be activated. And the relevant avoiding action of the case will be provided for navigators. The process is called 'Scene Matching' in ESCAN. Moreover, navigators can also browse these cases in ESCAN and select the similar ones to deal with current situation. This provides an auxiliary approach for solving the lack of experience of young seafarers under multi-ship encountering situations to some extent. However, it should be noted that some of actions of the cases are simple and effective, but they also do not strictly conform to COLREGS. And if such actions are taken and lead to collide with other ship, own ship will take the blame for the collision. So the cases should be activated by strict 'Scene Matching', and the relevant avoiding actions of them are only for reference.

2.4.7 Approach for Dealing with Multi-target Situation in ESCAN

In ESCAN, considering the above six points(2.4.1~2.4.6), if own ship is involved in a multi-target encountering situation, ESCAN will analyze the encountering situations between she and other ships, and then predict possible movement of other ships, and then determine which target is the primary one to avoid, and then determine avoiding actions and the time to take them. Meanwhile, navigators should also consider the safe passing distance of current situation and the safe zone of collision avoidance provided by ESCAN. By using this approach, appropriate decision-making for dealing with current multi-target encountering situation of can be acquired.

Chapter 3 Design of ESCAN

According to the knowledge of collision avoidance discussed in chapter 2, design of ESCAN is introduced in this chapter.

3.1 Design of Integrated Structure

3.1.1 External Connection of ESCAN

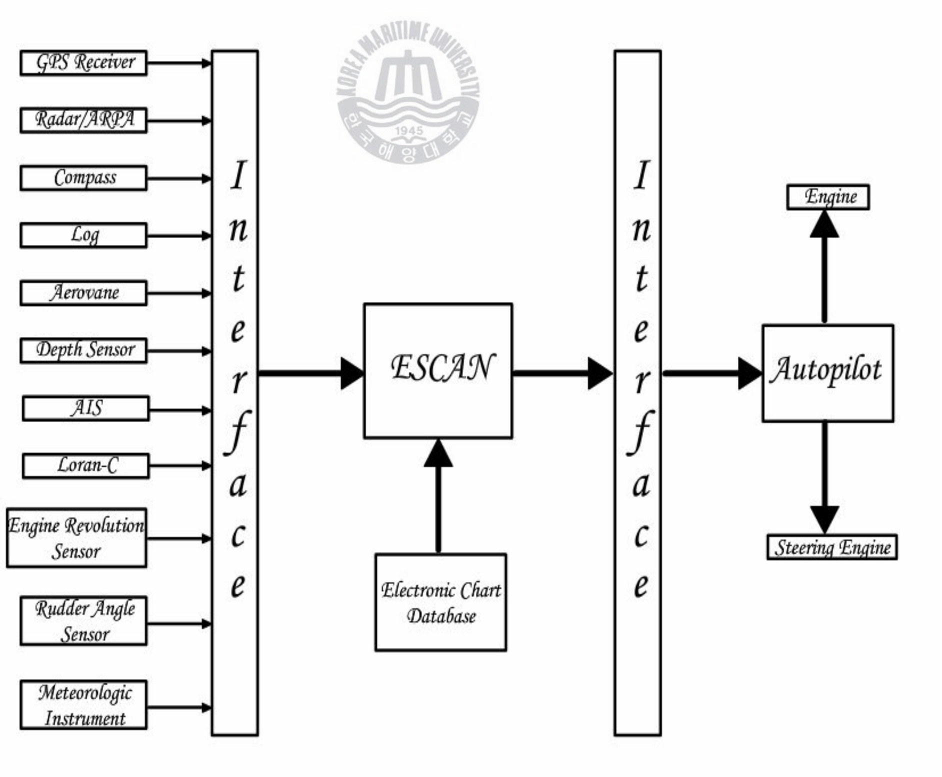


Fig.3-1 Connection Diagram of ESCAN with Navigational Equipment and Autopilot System

Ship automatic collision avoidance system contains two parts: software (application of ESCAN) and external hardware (interface circuits and navigational equipment). In Fig.3-1, external connection diagram of ESCAN is shown. As the center of an automatic decision-making system for collision avoidance, ESCAN draws inferences according to the data from navigational equipment such as AIS receiver. When date are acquired from navigational equipment through interface circuit, information can be extracted, calculated according to them and be preserved in ESCAN. Some data, such as position information of a target, only need to be extracted from character strings from AIS receiver. On the other hand, other information needs to be calculated, for example, approaching time of a target. All these data are important because they are used for premises and conditions in drawing inferences. When decision for collision avoidance is determined, detailed orders of avoiding action can be given to autopilot so as to implement automatic collision avoidance. Of course, considering present technologies of this field, manual intervention is still important during the process of automatic collision avoidance. During navigation, not only ships in the vicinity of own ship but also all kinds of obstacles which can effect the navigation of own ship should be considered. Usually, the obstacles are reefs, islands, navigation marks, buoys and so on. And the information of them can be acquired by searching database of electronic navigational charts (ENC[13]).

[13] An electronic navigation chart (ENC) is an official database created by a national hydrographic office for use with an Electronic Chart Display and Information System (ECDIS). An electronic chart must conform to standards stated in the International Hydrographic Organization (IHO) Special Publication S-57 before it can be certified as an ENC. Only ENCs can be used within ECDIS to meet the IMO performance standard for ECDIS.

3.1.2 Structure of ESCAN

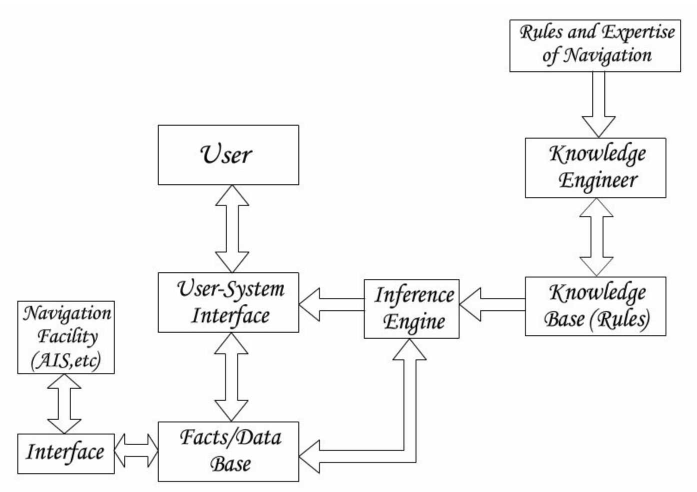


Fig.3-2 Structure of ESCAN

As shown in Fig.3-2, the structure of ESCAN mainly consists of four parts: Facts/Data Base, Knowledge Base, Inference Engine and User-System Interface[23].

Facts/Data Base (hereafter 'FB') is in charge of preserving data received from navigational equipment. Before the data are preserved into FB, they should be transformed into facts according to the format of CLIPS. FB is a global base of facts used by the rules and is the database of decision-making for collision avoidance. Facts of ESCAN include several types such as fact of own ship, fact of target, fact of visibility and so on.

Knowledge Base (hereafter 'KB') is to store production rules of ESCAN. Building the KB of ESCAN is to use a proper method to represent navigational knowledge and expertise. The ability of an expert system lies on the quantity and quality of the knowledge in the KB of it. Knowledge in ESCAN is collected from

COLREGS, comments and explanation of it, navigation experts and so on. The knowledge should be extracted, induced and processed into CLIPS-format rules and stored in KB. Production rules in KB are used for inferences drawn by Inference Engine. Moreover, some math functions for calculating are also stored in KB.

Inference Engine (hereafter 'IE') is an overall mechanism for controlling the execution of production rules in ESCAN. IE draws inferences by deciding which rules in KB are satisfied by facts in FB, prioritizes the satisfied rules, and executes the rule with the highest priority. That is to say, IE can draw inferences by judging which rules should be executed and when. IE is a control center of execution of production rules and is in charge of operation and control of the whole system of ESCAN. It is the 'Brain' of ESCAN.

User-System Interface (hereafter 'USI') is for communication between users and ESCAN. USI can convert the commands or data input by users into the format of CLIPS, and clearly display the results of inferences and additional advice and recommendation provided by ESCAN. Users can distinctly acquire the decision of collision avoidance for current situation or some other navigational information of other ships in the vicinity of own ship through USI.

3.2 Design of Facts/Data Base

In ESCAN, facts are pieces of navigational information extracted from data from navigational equipment and are the data basis for inferences.

In order to draw inferences of collision avoidance or display navigational information, ESCAN should be able to receive data from various kinds of navigational equipment. Ordinarily, shipborne navigational equipment and the data that they can provide are as follows:

(1) GPS Receiver – GMT[14], SOG (Speed Over Ground), COG (Course Over Ground), Position (Latitude and Longitude) of own ship.

(2) Radar/ARPA – Distance from a target, Relative Course of a target, Relative Bearing of a target, True Course, True Bearing, *DCPA*, *TCPA* and so on.

(3) Compass (Gyro/Magnetic) – Heading of own ship, Course of own ship, Bearing of a target.

(4) Log – Log Speed.

(5) Aerovane – Speed of wind, Direction of wind.

(6) Depth Sensor – Depth of water

(7) AIS Receiver – Position (Latitude and Longitude), Call Sign, MMSI number, Speed, Course, Heading, Type, Length, Breadth and so on of a target.

(8) Loran-C – Target's Position

(9) Engine Revolution Sensor – RPM (Revolution Per Minute) of Main Engine

(10) Rudder Angle Sensor – Rudder Angle of own ship

(11) Weather Instrument – Information of weather, Sea Conditions (tide, wave, current).

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[14] Greenwich Mean Time (GMT) is a term originally referring to mean solar time at the Royal Observatory in Greenwich, London. It is now often used to refer to Coordinated Universal Time (UTC) when this is viewed as a time zone.

Not all the facilities are equipped on each ship, but they should be connected with ESCAN if they are available on board for providing sufficient information for decision-making of collision avoidance.

In ESCAN, data received from navigational equipment can not be used directly and they are only character strings in different formats. In ESCAN, the facts are in CLIPS-format, contain useful information extracted from these data and are preserved in FB. And these facts are to be used by production rules in KB.

Every piece of extracted useful information can be preserved in a fact. In ESCAN, some important types of fact are introduced as follows:

(1) Fact of own ship

Collision avoidance mainly happens between own ship and target-ships, the two kinds of facts are the most important types of facts in ESCAN. Obviously, at the same time, only one fact of own ship can exist but number of fact of target-ship can be zero or more. Fact of own ship can be defined as follows:

OwnShip:: Name, Call_Sign, Course_Sector, Speed_Sector, Heading_Sector, Give_Way_Sign;

OwnShipInfo:: Name, Call_Sign, Course, Speed, Heading

In ESCAN, the process of decision-making needs a period of time. Updating intervals of data may be so small that they are not enough to implement the process of complicated decision-making. Obviously, if ESCAN always starts a new process of decision-making when any data are updated, it may be overloaded and collapse. In fact, this high-frequency of decision-making is not necessary and the decision-making will be identical or very similar in a short period of time because the encountering situation will not change until the data enter the data range of another different encountering situation. So it is necessary to separate the data for decision-making from the data updated in real-time and to design fact type *OwnShip* and fact type *OwnShipInfo* to record them respectively. Static data and sector marks of navigational data of own ship are recorded in the fact of *OwnShip* and the sector marks will be updated when relevant data enter another sector. The data updated in real-time are recorded in the fact of *OwnShipInfo*. In this way, unnecessary redundant decision-making can be reduced so as to improve the efficiency of ESCAN.

(2) Fact of Target

Similarly, fact of target-ship can be defined as follows:

Target :: Name, Call_Sign, MMSI number, Distance_Sector, Course_Sector, Speed_Sector, Heading_Sector, Encountering_State, Give_Way_Sign;

TargetInfo:: Name, Call_Sign, MMSI number, Distance, Course, Speed, Heading, DCPA, Approaching_Time, Collision_Risk_Value, Approaching_Speed, Aspect, Relative_Bearing

(3) Some other kinds of facts, like fact of obstacle, can be defined as follows:

Obstacle:: Sign_Name, Type_Of_Obstacle, Bearing_Sector

ObstacleInfo:: Sign_Name, Bearing

In the definitions of facts, '::' means separator of type. And meaning of every field of facts is shown just as meaning of its name.

3.3 Design of Knowledge Base

3.3.1 Sources of the Knowledge of Collision Avoidance

Knowledge is the foundation of intelligence activities. The performance level and capability of an expert system lie on the abundance and quality of knowledge in it. Building an expert system is to acquire the knowledge of a specific domain and utilize it for instructing other people.

Considering the developing level of expert system, it is hard to acquire knowledge automatically by using on-line studying program. Most successful expert systems still use non-automatic data acquiring approaches. Between expert system and outside sources of knowledge, knowledge engineers are needed to implement the collection and conversion of knowledge. Knowledge engineers collect the knowledge of collision avoidance by researching COLREGS and other materials of collision avoidance, communicating with navigation experts, analyzing common approaches for dealing with collision avoidance, and understanding the specialties of thought of these experts. And then they use proper and accurate words to summarize the knowledge. Finally, these words are converted into CLIPS-format production rules. These rules are stored in KB. In ESCAN, navigational knowledge is based on COLREGS and other navigation expertise materials including Jeong's study [17]. In ESCAN, the sources of Knowledge Base are as follows:

(1) Elementary knowledge of collision avoidance acquired from COLREGS [5], [27]. COLREGS is the basic guide line of collision avoidance. It regulates three basic encountering situations (head-on, crossing, and overtaking), relevant obligations and responsibilities and so on when ships are in sight of one another. It also provides the navigational conduct of ships in restricted visibility conditions.

(2) Heuristic knowledge acquired from navigation expertise [27].

(3) Explanations and comments of COLREGS made by experienced shipmasters, navigators and other experts [5].

(4) Explanations of collision cases made by navigation experts and maritime tribunals [1].

(5) Experience of practical good seamanship [47], [49], [51].

(6) Statistic of behaviors of navigators for dealing with collision avoidance [29], [30].

(7) Sophisticated avoiding actions of typical multi-ship encountering scenes in materials [2], [32].

(8) Statistic and analysis results of collision cases [52].

3.3.2 Process of Building Knowledge Base

The task of building KB is implemented by knowledge engineers. The process of building KB is shown in Fig.3-3 and can be explained as follows:

Step 1: Knowledge engineers analyze and extract useful knowledge from related materials.

Step 2: Knowledge engineers formalize the acquired knowledge into rules.

Step 3: Rules are converted into CLIPS-format production rules.

Step 4: Testing rules. If result of testing of a rule is not appropriate then process goes to *Step 5*. Otherwise rules are stored in KB.

Step 5: Supplementing and modifying the improper rules. Then process goes back to *Step 4*.

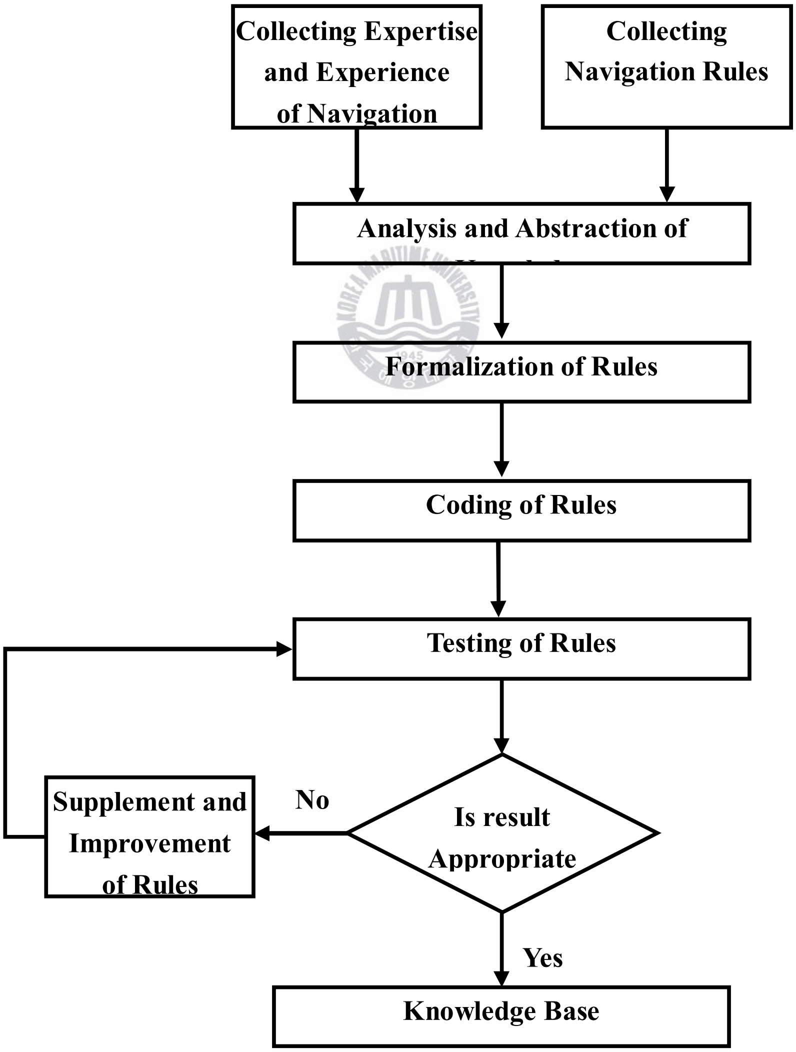


Fig.3-3 Process of Building Knowledge Base

Knowledge base should be updated regularly because knowledge of collision avoidance increases all the time.

3.3.3 Module Structure of Knowledge Base

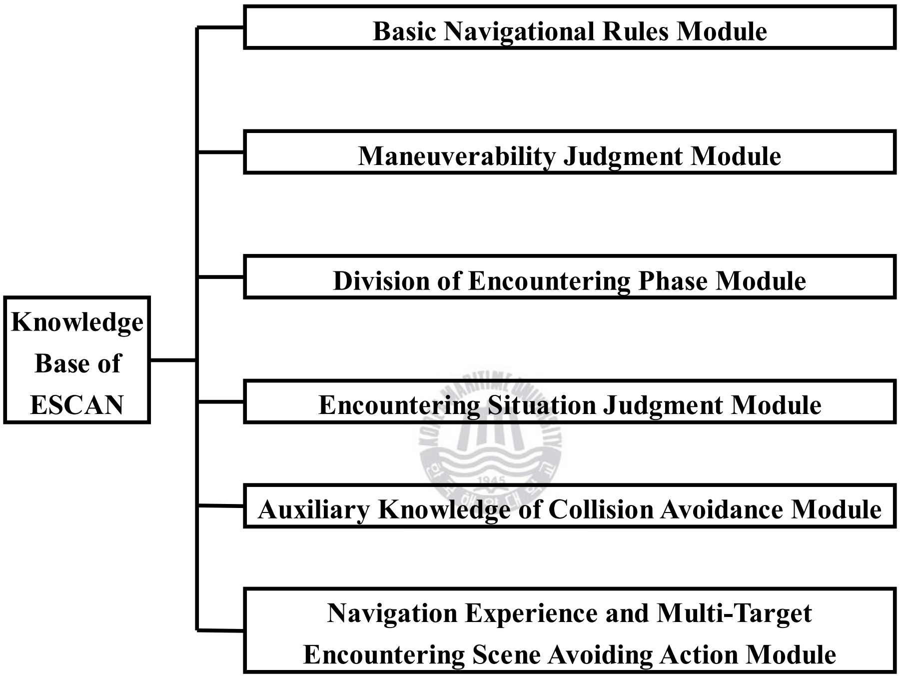


Fig.3-4 Module Structure of Knowledge Base

KB is a main intelligent component of decision-making system and plays an important role in every expert system. A well-designed structure of KB can improve the efficiency of inference engine. So it is important that the KB of ESCAN has a well-designed structure.

In this paper, module structure is used to construct the KB of ESCAN. As shown in Fig.3-4, KB of ESCAN is divided into six modules, and every module contains several related aspects. These six modules are independent of each other and are able to adapt to forward inference and backward inference. During the process of inference, if some knowledge is needed, the module which contains the knowledge will be chosen as current module for accomplishing the relevant inference by IE. The whole process of inference is controlled by IE. Module structure of KB is not only favorable for exerting and improving efficiency of inference, but also favorable for organizing, managing, maintaining and upgrading it.

Detailed description of every module of KB is as follows:

(1) Basic Navigational Rules Module

It contains basic regulations of COLREGS, and comments and explanations of COLREGS made by navigational experts [5]. Detailedly, it can be divided into three aspects as follows:

(a) Basic rules. The rules of collision avoidance are for ships in sight of one another.

(b) Rules for bad weather. The rules of collision avoidance are for bad sea conditions such as restricted visibility, huge wave and so on.

(c) Rules for restricted areas. The rules are for restricted areas, for example narrow channel.

(2) Maneuverability Judgment Module

With use of AIS equipment on board, ships are able to receive navigational information from other ships in the vicinity of them. The information contains width, length, type of a target and so on. Own ship can use general maneuverability of each type of ships and the information of a target to extrapolate its rough maneuverability [39].

(a) Rules for judging rough specialities of approaching targets. The specialties of each type of ships (tanker, container ship, bulk ship and so on) are preserved. When own ship detects a target and knows its type, and if ESCAN can find the specialities of the relevant type of it, and then own ship can know the rough maneuverability of it.

(b) Rules for preserving the equations of maneuverability of specific ships. If equations of maneuverability of a specific ship are preserved, more accurate indices of maneuverability of it can be acquired by adjusting related parameters.

(c) Rules for determining parameters of equations. Criterions and references for determining the parameters of equations of maneuverability are preserved.

(3) Division of Encountering Phase Module

(a) Rules for judging phase of effect-free action. Rules for judging that no collision risk exists between own ship and targets.

(b) Rules for judging phase of involving collision risk. Rules for judging that own ship becomes involved in collision risk with other target, the stand-on ship should keep her course and speed, and the give-way ship should positively take substantial avoidance action.

(c) Rules for phase of close-quarters situation. Rules for judging that own ship becomes in close-quarters situation with other target.

(d) Rules for phase of danger of collision. Rules for judging that own ship and other target become involved in danger of collision.

(4) **Encountering Situation Judgment Module**

(a) Based on Fig.2-4, rules for judging encountering situations (head-on, crossing and overtaking) between two ships in sight of one another.

(b) Rules for judging encountering situations when two ships are not in sight of one another. Rules for ships in sight of one another can also be used in this situation for reference. But the obligation of stand-on ship to keep her course and speed no longer exists.

(5) Auxiliary Knowledge of Collision Avoidance Module

(a) Rules for appraising value of collision risk. According to some specific mathematic models, value of collision risk of a target can be calculated. Different models may be used so that users can select a proper one to use.

(b) Rules for predicting actions of targets. According to the known information of a target, its following action can be predicted.

(c) Rules for determining the timing to take avoiding actions. According to current conditions and environment, timing to take avoiding actions can be determined.

(d) Rules for selecting the primary target-ship to avoid. According to the values of collision risk of each target, one target-ship which has the maximum value of collision risk can be chosen as the primary avoiding target-ship.

(6) Navigation Experience and Multi-ship Encountering Scene Avoiding Action Module

(a) Rules for emergencies [46]. For example, when collision between own ship and target-ship can not be avoided, some actions departing from COLREGS may be used to reduce the loss of collision.

(b) Rules for using typical cases of multi-ship collision avoidance with good seamanship [1]. Rules for preserving the simple and effective avoiding actions made by experienced experts for dealing with some typical cases of multi-ship collision avoidance and rules for activating a specific case for dealing with current situation are stored in this module.

Collision avoidance is very complicated. So during the process of decision-making of collision avoidance, in addition to principles of navigation (Basic Navigational Rules Module), maneuverability of own ship and targets (Maneuverability Judgment Module), encountering phase (Division of Encountering Phase Module), encountering situation (Encountering Situation Judgment Module) and timing to take avoiding action (Auxiliary Knowledge of Collision Avoidance Module) also need to be considered.

Module structure preserves different knowledge in different modules and is easy to be organized and administrated. But because the available materials are limited, knowledge of some aspects in these modules is insufficiency or absent. However, Rome was not built in one day. KB also needs to be upgraded gradually. With the development and research of collision avoidance, new knowledge can be collected and added into KB of ESCAN. Knowledge engineer should keep collecting knowledge of collision avoidance to upgrade the KB so as to provide more high-quality knowledge for decision-making of collision avoidance.

3.3.4 Knowledge Representation

3.3.4.1 Basic Requirement of Knowledge Representation

In an expert system, knowledge representation is to code facts, relationships and processes of the world into a proper data structure. It is a symbolizing process of knowledge. Knowledge representation should select a proper approach to represent, that is to say, to find a proper mapping between the knowledge and its representation.

Production rules, semantic nets, schemata, frames, and logic are common approaches by which knowledge is represented in expert systems. Knowledge representation is of major importance in expert systems for two reasons. First, expert system shells are designed for a certain type of knowledge representation such as rules or logic. Second, the way in which an expert system represents knowledge affects the development, efficiency, speed and maintenance of the system. Because production rules are perfect for representing the knowledge of collision avoidance and CLIPS is a tool supporting them well, production rules are used to represent the knowledge in ESCAN. Some detailed reasons are as follows:

(1) Similarity to the human cognitive process. Production rules appear to be a natural way of modeling how humans solve problems. The simple

*IF…THEN…*representation of rules makes it easy to explain to experts the structure of the knowledge you are trying to elicit from them.

(2) Fully representing knowledge. To determine a method for representing knowledge, it is should be firstly considered whether the method can fully represent relevant domain knowledge. So it is important to know the specialities of the domain knowledge. In ESCAN, knowledge of collision avoidance is quite stable and has causal relationship, so it is appropriate to use production rules to present knowledge.

(3) Good for utilizing knowledge. Representing knowledge in expert system is to use it for drawing inferences so as to solve practical problems. So method for representing knowledge should fit in with the mode of operation of inference engine so as to exert its maximum efficiency. In ESCAN, forward chaining inference supported by CLIPS is used in IE, and IE can work efficiently by implementing the production rules representing knowledge of collision avoidance.

(4) Having proper data structure. Production rules are not only in accordance with thinking habits of human, but also easy to be understood. An important specialty of them is modular nature. This makes it easy to encapsulate knowledge and expand the expert system by incremental development. Format of production rules is fixed and simple, and knowledge encapsulated in the antecedents and consequents of them is not much. This is convenient for building a KB of collision avoidance and also convenient for checking consistency and integrality of the knowledge in it. If the data structure of a method for representing knowledge is so complicated that it is difficult to be understood and implemented, it will greatly

influence the efficiency of expert system and reduce its ability on problem-solving. During long-term operation of an expert system, some problems may appear on the aspect of quality of knowledge. New knowledge or modification of original knowledge may need to be supplemented in KB. Because production rules have simple structure, maintenance and management of knowledge in KB is easy to be implemented.

(5) Explanation facilities. It is easy to build explanation facilities with rules because the antecedents of a rule specify exactly what is necessary to activate the rule. By keeping track of which rules have fired, an explanation facility can present the chain of reasoning that led to a certain conclusion.

3.3.4.2 Knowledge Representation in ESCAN

In ESCAN, a knowledge base with module structure discussed in section 3.3.3 is built. Although all six modules use production rules to represent knowledge, they are independent on storage and functions. Especially, each module has clearly different functions. This is convenient for implementing the preservation and maintenance of knowledge in KB.

A production rule can be abstractly described as a unit containing two elements: one element can be explained as the description of conditions, and the other one can be explained as the description of related actions or consequent. This kind of unit composed of conditions and actions can be expressed as follows:

<Antecedent> → *<Actions or Consequent>*

It can be expressed as: *IF [P]* *THEN [Q]*

Or simply: $P \rightarrow Q$

Here, '$\rightarrow$' is a mark of deduction and means *P* can deduce *Q*.

'*P*' is the antecedent of a rule and is a set of conditions (or conditional elements) which must be satisfied for the rule to be applicable. And it is also referred to as the 'if portion' or the 'left-hand side (LHS)' of the rule. In CLIPS, the conditions of a rule are satisfied base on the existence of specified facts in the fact-list. One type of condition which can be specified is a pattern. Patterns consist of a set of restrictions which are used to determine which facts satisfy the condition specified by the pattern. The process of matching facts to patterns is called pattern-matching.

'*Q*' is the consequent of a rule and is the set of actions to be executed when the rule is applicable. And it is also referred to as the 'then portion' or the 'right-hand side (RHS)' of the rule. The actions of applicable rules are executed when inference engine is instructed to begin execution of applicable rules. If more than one rule is applicable, the inference engine uses a conflict resolution strategy to select which rule should have its actions executed. The actions of the selected rule are executed (which may affect the list of applicable rules) and then the inference engine selects another rule and executes its actions. This process continues until no applicable rules remain.

In many ways, rules can be thought of as *IF-THEN* statements found in procedural programming. However, the conditions of an *IF-THEN* statement in a procedural language are only evaluated when the program flow of control is directly at the *IF-THEN* statement. In contrast, rules act like *WHENEVER-THEN* statements. The inference engine always keeps track of rules which have their conditions satisfied and thus rules can immediately be executed when they are applicable.

When antecedent and consequent of a rule are expressed by first-order prediction logic, a production rules knowledge system can be expressed as follows:

< Production rule knowledge system > ::= < Production rule >+

< Production rule > ::= < Antecedent > → *< Action >**

*< Antecedent > ::= < Predicate >**

< Action > ::= <Action-name>{<Action-element>+}

< Predicate > ::= <Predicate-name> {<Predicate-element>+}

Here, sequences of words enclosed in single-angle brackets, such as *<Predicate>*, represent a single entity of the named class of items to be supplied. A non-terminal symbol followed by a '*', represents *zero or more* entities of the named class of items which must be supplied. A non-terminal symbol followed by a '+', represents *one or more* entities of named class of item which must be supplied. Curly braces represent a set of the elements. The '*::=*' symbol is used to indicate how a non-terminal symbol can be replaced.

Some specialities of production rules are as follows:

(1) Same condition can deduce different consequents, for example $A \rightarrow B$, $A \rightarrow C$. In the field of collision avoidance, for example, in some situations, own ship can choose reduce her speed or substantially alter her course.

(2) Same consequents can be deduced from different conditions, for example

$A \rightarrow G$, $B \rightarrow G$. This point is easy to be understood, for example, alteration of course can be deduced from different conditions.

(3) Conditions of a rule can be plural and be linked by '*AND*' and '*OR*', or symbols '$\wedge$' and '$\vee$'. For example, $A \wedge B \rightarrow G$, $A \vee B \rightarrow F$.

(4) Consequent of a rule can be a condition of another rule. For example, $C \vee D \rightarrow F$, $F \wedge B \rightarrow G$. In the field of collision avoidance, consequent of a judgment of encountering situation between own ship and a target-ship can be a condition of the rule which can determine the relevant avoiding actions.

Knowledge of collision avoidance can be described as *'IF…THEN…'* statements or *'WHEN…THEN…'* statements. For example, '*When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.*';' *When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if circumstances of the case admit, avoid crossing ahead of the other vessel.* ' So it is proper to use production rules to represent the knowledge of collisions avoidance.

In this section, antecedent of production rules of collision avoidance can be described by predicates.

Firstly, if maneuverability is not considered, fifteen predicates can be defined to simply describe the basic states of ships as follows:

< Predicate > ::= P1 | P2| P3| P4| P5| P6| P7| P8| P9| P10| P11| P12| P13| P14| P15

The fifteen predicates can be described as follows:

(1) *P1*: Encountering situation descriptor that describes encountering situations when two ships encounter.

P1 = {<Head_On_Port>, <Head_On_DeadAhead_Starboard>,

< Crossing_Port_Forward_Beam>, <Crossing_Port_Abeam>,

<Crossing_Port_Abaft_Beam>, <Crossing_Starboard_Forward_Beam>,

<Crossing_Starboard_Abeam>, <Crossing_Starboard_Abaft_Beam >

<Overtaking_Port>, <Overtaking_Starboard>,

<Overtaken_Port>, <Overtaken_Starboard>}

P1 not only describes different situations when ships encounter, but also defines these situations according to different values of bearing of a target θ. The θ areas of different situations are shown in Table 3-1.

Table 3-1 Divisions of Encountering Situation

Encountering Situation	Subdivision of Encountering Situation	Value Area of θ (º)
Head-On	Head_On_Port	$\theta \in [354^\circ, 360^\circ)$
	Head_On_DeadAhead_Starboard	$\theta \in [0^\circ, 6^\circ]$
Crossing_Port	Crossing_Port_Forward_Beam	$\theta \in (6^\circ, 67.5^\circ]$
	Crossing_Port_Abeam	$\theta \in (67.5^\circ, 100^\circ]$
	Crossing_Port_Abaft_Beam	$\theta \in (100^\circ, 112.5^\circ]$
Crossing_Starboard	Crossing_Starboard_Forward_Beam	$\theta \in [292.5^\circ, 354^\circ)$
	Crossing_Starboard_Abeam	$\theta \in [260^\circ, 292.5^\circ)$
	Crossing_Starboard_Abaft_Beam	$\theta \in [247.5^\circ, 260^\circ)$
Overtaking	Overtaking_Port	$\theta \in [0^\circ, 67.5^\circ)$
	Overtaking_Starboard	$\theta \in (292.5^\circ, 360^\circ)$
Overtaken	Overtaken_Port	$\theta \in (180^\circ, 247.5^\circ)$
	Overtaken_Starboard	$\theta \in (112.5^\circ, 180^\circ]$

(2) ***P2*****: Relative bearing descriptor that describes relative bearing of a target to own ship.**

P2 = {< Bearing_Sector_1>, < Bearing_Sector_2>, … ,

< Bearing_Sector_24>, < Bearing_Sector_25>}

In ESCAN, relative bearings are divided into 25 areas as shown in Table 3-2.

Table 3-2 Divisions of Relative Bearing

Divisions of Relative Bearing	**Value Area of θ ($^{\circ}$)**
RBearing_Sector_1	$\theta \in [0^{\circ}, 6^{\circ}]$
RBearing_Sector_2	$\theta \in (6^{\circ}, 20^{\circ}]$
RBearing_Sector_3	$\theta \in (20^{\circ}, 35^{\circ}]$
RBearing_Sector_4	$\theta \in (35^{\circ}, 50^{\circ}]$
RBearing_Sector_5	$\theta \in (50^{\circ}, 67.5^{\circ}]$
RBearing_Sector_6	$\theta \in (67.5^{\circ}, 80^{\circ}]$
RBearing_Sector_7	$\theta \in (80^{\circ}, 95^{\circ}]$
RBearing_Sector_8	$\theta \in (95^{\circ}, 112.5^{\circ}]$
RBearing_Sector_9	$\theta \in (112.5^{\circ}, 125^{\circ}]$
RBearing_Sector_10	$\theta \in (125^{\circ}, 140^{\circ}]$
RBearing_Sector_11	$\theta \in (140^{\circ}, 155^{\circ}]$
RBearing_Sector_12	$\theta \in (155^{\circ}, 170^{\circ}]$
RBearing_Sector_13	$\theta \in (170^{\circ}, 185^{\circ}]$
RBearing_Sector_14	$\theta \in (185^{\circ}, 200^{\circ}]$
RBearing_Sector_15	$\theta \in (200^{\circ}, 215^{\circ}]$
RBearing_Sector_16	$\theta \in (215^{\circ}, 230^{\circ}]$
RBearing_Sector_17	$\theta \in (230^{\circ}, 247.5^{\circ})$
RBearing_Sector_18	$\theta \in [247.5^{\circ}, 260^{\circ})$
RBearing_Sector_19	$\theta \in [260^{\circ}, 275^{\circ})$
RBearing_Sector_20	$\theta \in [275^{\circ}, 292.5^{\circ})$
RBearing_Sector_21	$\theta \in [292.5^{\circ}, 325)$
RBearing_Sector_22	$\theta \in [310^{\circ}, 325)$
RBearing_Sector_23	$\theta \in [325^{\circ}, 340)$
RBearing_Sector_24	$\theta \in [340^{\circ}, 354)$
RBearing_Sector_25	$\theta \in [354^{\circ}, 360^{\circ})$

When relative bearing of a target does not change quickly, decisions of collision avoidance provided by ESCAN may be almost identical. So dividing the values into small sectors can reduce the redundant decision-makings which are determined by almost same conditions. This can effectively improve the efficiency of ESCAN.

(3) ***P3*****: Aspect angle descriptor that describes aspect angle of a target from own ship.**

P3 = {< Aspect_Head_On_Port>,

< Aspect_Head_On_DeadAhead_Starboard>,

< Aspect_Crossing_Port_Forward_Beam>,

< Aspect_Crossing_Port_Abeam>,

<Aspect_Crossing_Port_Abaft_Beam>,

<Aspect_Crossing_Starboard_Forward_Beam >,

< Aspect_Crossing_Starboard_Abeam >,

< Aspect_Crossing_Starboard_Abaft_Beam >

< Aspect_Overtaking_Port>,< Aspect_Overtaking_Starboard>,

< Aspect_Overtaken_Port>,< Aspect_Overtaken_Starboard>}

Conception of aspect angle α has been introduced in section 2.3.2.4. Aspect angles of targets are very important for judging encountering situations between own ship and target-ships. When a target locates a bearing to own ship, its aspect angle determined whether it is involved in collision risk and is involved in which encountering situation with own ship. For example, when a target's relative bearing is 30º and the distance from own ship is 2 nm, if its aspect angle is -150º, it is overtaken by own ship from port side as shown in Fig.3-5(a); if its aspect is -60º, it is involved in starboard abeam crossing situation with own ship as shown in Fig.3-6(b).

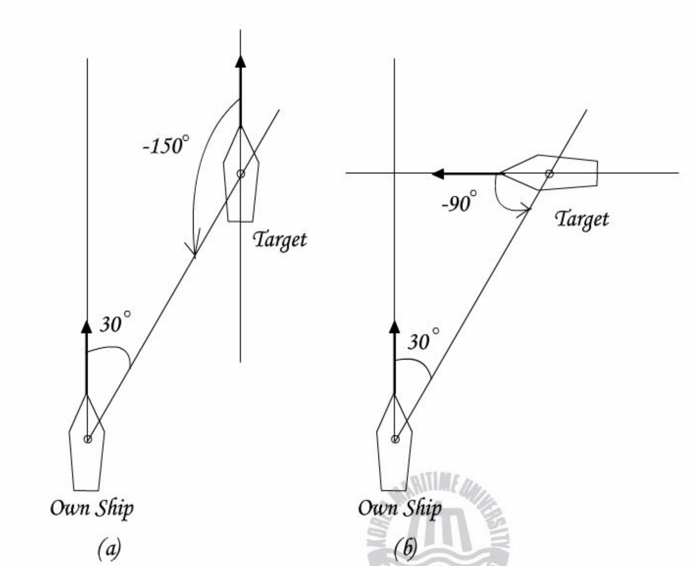


Fig.3-5 Different Encountering Situations with a Same Bearing

The α areas of different situations are shown in Table 3-3.

Table 3-3 Divisions of Aspect Angle

Encountering Situation	Subdivision of Encountering Situation	Value Area of α (º)
Head-On	Aspect_Head_On_Port	$\alpha \in$[-6º，6º]
	Aspect_Head_On_DeadAhead_Starboard	$\alpha \in$[-6º，6º]
Crossing_Port	Aspect_Crossing_Port_Forward_Beam	$\alpha \in$[-112.5º，0º]
	Aspect_Crossing_Port_Abeam	$\alpha \in$[-112.5º，0º]
	Aspect_Crossing_Port_Abaft_Beam	$\alpha \in$[-80º，0º]
Crossing_Starboard	Aspect_Crossing_Starboard_Forward_Beam	$\alpha \in$[0º，112.5º]
	Aspect_Crossing_Starboard_Abeam	$\alpha \in$[0º，112.5º]
	Aspect_Crossing_Starboard_Abaft_Beam	$\alpha \in$[0º，80º]
Overtaking	Aspect_Overtaking_Port	$\alpha \in$ [-180º，-112.5º]

	Aspect_Overtaking_Starboard	$\alpha \in$[112.5º, 180º]
Overtaken	Aspect_Overtaken_Port	$\alpha \in$[0º, 67.5º]
	Aspect_Overtaken_Starboard	$\alpha \in$[-67.5º, 0º]

According to Table 3-3, own ship can judge whether a target-ship is involved in collision risk with her, or which subdivision of encountering situation is formed with the target-ship. That is to say, an encountering situation between own ship and a target-ship is determined by relative bearing θ and aspect angle of the target α.

(4) *P4*: Distance descriptors which describe distance between own ship and target-ships.

P4 = {< Distance_Level_1>, < Distance_Level_2>, … ,

< Distance_Level_7>, < Distance_Level_8>, < Distance_Level_Out>}

In ESCAN, distance between own ship and a target-ship is divided into small distance levels as shown in Table 3-4.

Table 3-4 Distance Level

Distance Level Tag	Value Area of Distance (nm)
Distance_Level_1	$D \in$[0, 1]
Distance_Level_2	$D \in$(1, 2]
Distance_Level_3	$D \in$(2, 3]
Distance_Level_4	$D \in$(3, 4]
Distance_Level_5	$D \in$(4, 5]
Distance_Level_6	$D \in$(5, 6]
Distance_Level_7	$D \in$(6, 8]
Distance_Level_8	$D \in$(8, 12]
Distance_Level_Out	$D > 12$

Usually, when distance from a target is less than 12 nm, own ship should begin to judge whether the target is dangerous.

(5) *P5*: Manoeuvring state descriptor which describes manoeuvring state of ships during the process of collision avoidance.

P5 = {< Give_Way_State >, < Stand_On_State >,

< Unable_Give_Way_State >,< Unable_Stand_On_State >}

The states are explained in Table 3-5

Table 3-5 Manoeuvring State

Manoeuvring State Tag	Meaning
Give_Way_State	The ship should take appropriate avoiding action to keep out of the way of the stand-on ship.
Stand_On_State	The ship should keep her course and speed.
Unable_Give_Way_State	The ship is not able to give way.
Unable_Stand_On_State	The ship is not able to stand on.

(6) *P6*: Sea area descriptor which describes where own ship are navigating.

P6 = {< Wide_Sea_Area >, < Narrow_Area >, < Port_Area >,< TSS_Area >}

In ESCAN, several sea areas are defined and explained in Table 3-6.

Table 3-6 Categories of Sea Areas

Sea Area Tag	Explanation
Wide_Sea_Area	Open Sea, Inshore wide area
Narrow_Area	Narrow channel
Port_Area	Area near port.
TSS_Area	Traffic separation schemes area.

(7) *P7*: Traffic situation descriptor which describes traffic situation in the vicinity of own ship.

P7 = {< Traffic_Excellent >, < Traffic_Good >, < Traffic_Busy >,< Traffic_VeryBusy >}

In ESCAN, several traffic situations are used and explained in Table 3-7.

Table 3-7 Traffic State

Traffic Situation Tag	**Explanation**
Traffic_Excellent	Traffic situation is excellent in the vicinity of own ship.
Traffic_Good	Traffic situation is Good in the vicinity of own ship.
Traffic_Busy	Traffic situation is Busy in the vicinity of own ship.
Traffic_VeryBusy	Traffic situation is Very Busy in the vicinity of own ship.

(8) *P8*: Speed relationship descriptor which describes speed ratio between own ship and a target-ship.

K is used to describe the speed ratio. *K* is defined as $K = \frac{V_T}{V_O}$, V_T is speed of target-ship, V_O is speed of own ship.

P8 = {< K_Level_1 >, < K_Level_2 >, < K_Level_3 >}

In ESCAN, value of *K* can be defined as three levels as shown in Table 3-8.

Table 3-8 Speed Ratios

Level of *K*	**Value Area of *K***
K_Level_1	$K<=1$
K_Level_2	$1<K<=2$
K_Level_3	$K>2$

(9) *P9*: Visibility description which describes the visibility own ship has.

P9 = {< Visibility_Excellent >, < Visibility_Good >, < Visibility_Normal >,

< Visibility_Poor >, < Visibility_Bad >, < Visibility_Worst >}

In ESCAN, 6 levels of visibility are defined as shown in Table 3-9.

Table 3-9 Level of Visibility

Level of Visibility	Explanation
Visibility_Excellent	Visibility is more than 15 miles.
Visibility_Good	Visibility is more than 10 miles and less than 15 miles.
Visibility_Normal	Visibility is more than 6 miles and less than 10 miles.
Visibility_Poor	Visibility is less than 6 miles and more than 2 miles.
Visibility_Bad	Visibility is less than 2 miles and more than 1 mile.
Visibility_Worst	Visibility is less than 1 mile.

Subdividing visibility is to detailedly describe the visibility condition which own ship has. In the future, more specific rules can be developed to deal with the collision avoidance situations in different levels of visibility.

(10)*P10*: Action execution descriptor which shows whether own ship is taking avoiding action.

Because if own ship is taking an avoiding action, ordinarily, own ship should finish this action. Otherwise, other ships may misunderstand the purpose of own ship so as to cause worse situation.

P10 = {<Avoiding_Action_Executing>}

Value of the descriptor is explained in Table 3-10

Table 3-10 Value of Action Execution Descriptor

Value of Avoiding_Action_Executing	Explanation
TRUE	Avoiding Action is executing.

FALSE	No action is executing.

(11) ***P11*****: Avoiding action validation descriptor which shows whether an avoiding action of own ship is valid.**

That is to say, the descriptor shows whether the action has effectively reduced collision risk between own ship and a target-ship.

P11 = {<Avoiding_Action_Validation>}

Value of the descriptor is explained in Table 3-11.

Table 3-11 Value of Avoiding Action Validation Descriptor

Value of Avoiding_Action_Validity	Explanation
TRUE	Action is valid.
FALSE	Action is not valid.

(12) ***P12*****: Keeping clear descriptor which shows whether own ship has kept well clear off a target-ship.**

If own ship does so, value of the descriptor is true and own ship should return to original course and route in time. Otherwise, own ship should keep her course.

P12 = {<Target_Clear>}

Value of the descriptor is explained in Table 3-12.

Table 3-12 Value of Keeping Clear Descriptor

Value of Target_Clear	Explanation
TRUE	Own ship has already kept well clear.
FALSE	Own ship hasn’t keep well clear yet.

(13)*P13:* Multi-ship encountering situation descriptor which shows whether own ship is involved in multi-ship encountering situation with other targets.

P13 = {<Multi_Target_Flag>}

Value of the descriptor is explained in Table 3-13.

Table 3-13 Value of Multi-ship Encountering Situation Descriptor

Value of Multi_Target_Flag	**Explanation**
TRUE	Own ship gets into multi-target meeting situation.
FALSE	Own ship does not get into multi-target meeting situation

If the value of this descriptor is true, ESCAN starts select the primary target-ship to avoid and trigger matching function of typical multi-ship encountering scenes for providing navigators with more useful information.

(14)*P14*: Multi-ship encountering situation descriptor which shows how many targets that own ship is encountering in the vicinity of her.

P14 = {< Multi_Target_2>, <Multi_Target_3>,…,

<Multi_Target_14>, <Multi_Target_15>}

Usually, number of ships which are involved in multi-ship encountering situation is less than 10. In ESCAN, maximum value of the number is set to be 15. And the detailed content of the descriptor is shown in Table 3-14.

Table 3-14 Multi-ship Encountering Situation Descriptor

Multi_Target_2	Own ship is encountering 2 targets.
Multi_Target_3	Own ship is encountering 3 targets.
……	……

Multi_Target_14	Own ship is encountering 14 targets.
Multi_Target_15	Own ship is encountering 15 targets.

(15)*P15*: Type of ship descriptor which describes different types of ship according to Rule 18 of COLREGS.

P15 = {<Power_Driven_Vessel>,<Sailing_Vessel> ,

< Vessel_Engaged_Fishing >,< Vessel_Restricted_Manoeuver >,

< Vessel_Not_Under_Command >,<Vessel_Constrained_Draught>}

In Rule 18 of COLREGS, responsibilities between different types of vessels are regulated [48] as shown in Fig.3-6.

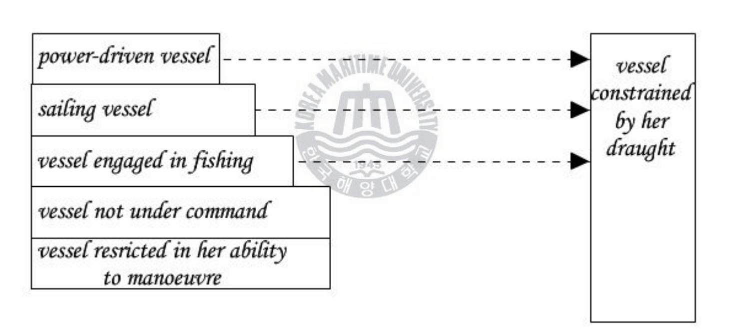


Fig.3-6 Responsibilities between Vessels

In Fig.3-6, upper ship should keep out of the way of lower ship; dash line means the left vessel should avoid impeding the right vessel. In ESCAN, the detailed contents of the descriptor are shown in Table 3-15.

Table 3-15 Type of Ship Descriptor

Vessel Sort	Explanation
Power_Driven_Vessel	Any vessel propelled by machinery.
Sailing_Vessel	Any vessel under sail provided that propelling machinery, if fitted, is not being used.
Vessel_Engaged_Fishing	Any vessel fishing with nets, lines,

	trawls or other fishing apparatus which restrict manoeuvrability, but does not include a vessel fishing with trolling lines or other fishing apparatus which do not restrict manoeuvrability.
Vessel_Restricted_Manoeuver	A vessel which from the nature of her work is restricted in her ability to manoeuvre as required by these Rules and is therefore unable to keep out of the way of another vessel.
Vessel_Not_Under_Command	A vessel which through some exceptional circumstance is unable to manoeuvre as required by these Rules and is therefore unable to keep out of the way of another vessel.
Vessel_Constrained_Draught	A power-driven vessel which because of her draught in relation to the available depth and width of navigable water is severely restricted in her ability to deviate from the course she is following.

Until now, the 15 descriptors for describing the basic states of ships are fully introduced.

Then descriptors of actions are introduced as follows. Here, actions contains two types: basic actions and heuristic actions, that is

<Action> :: = <Action_Basic> | *<Action_Heuristic >*

<Action_Basic> is a set which contains basic and common avoiding actions.

< Action_Basic > ={<Course_Alteration>,<Speed_Alteration>

,<CourseAndSpeed_Alteration>}

<Course_Alteration> = {<Course_Alteration_Port >,

<Course_Alteration_Starboard >}

<Speed_Alteration> = {<Speed_Increase>, <Speed_Decrease>,

<Engine_Stop>, <Engine_Reversion> }

<CourseAndSpeed_Alteration> = {<CAP_SI>, < CAP_SD>, <CAS_SI>,

< CAS_SD>,<CAP_ES>,<CAP_ER>

,<CAS_ES>,<CAS_ER> }

Explanations of these actions are shown in Table 3-16:

Table 3-16 Explanation of Basic Actions

Action	Subdivisions of Action	Explanation
Course_Alteration	Course_Alteration _Port	Alter course to port.
	Course_Alteration _Starboard	Alter course to starboard.
Speed_Alteration	Speed_Increase	Increase speed.
	Speed_Decrease	Decrease speed.
	Engine_Stop	Stop engine of vessel.
	Engine_Reversion	Reverse engine of vessel.
	CAP_SI	Alter course to port and increase speed.
	CAP_SD	Alter course to port and decrease speed.
	CAS_SI	Alter course starboard and increase speed.
	CAS_SD	Alter course starboard and decrease speed.
	CAP_ES	Alter course to port and stop engine.
	CAP_ER	Alter course to port and reverse engine.
	CAS_ES	Alter course to starboard and stop engine.
	CAS_ER	Alter course to starboard and reverse engine.

Concerning magnitude of detailed action, some level are defined in ESCAN as follows:

(1) Magnitude of alteration of course: One circle is divided into 36 equal parts, and every level is a part covering 10º. Detailed format is: *Action: Level_N*. 'Action' is a detailed action of alteration of course; '*Level_N*' is detailed magnitude of the action, 'N' means level of the magnitude. For example, '*Course_ Alteration _ Port: Level_4*' means the action is to alter course to port and magnitude of the action is 40º.

(2) Divisions of speed alteration. Usually, 4 levels of speed are used on board such as full speed, half speed, slow speed and dead slow speed. Half speed is 3/4 of full speed; slow speed 1/2 full speed; dead slow speed the minimum speed at which a vessel can be kept on her course. Engine operations are not further divided. Detailed format is *Action*: *Level*. 'Action' is a detailed speed alteration action; 'Level' is one level of the 4 speed levels. And all possible speed alteration actions are as follows:

Speed_ Increment: Full_Speed, *Speed_Increment: Half_Speed*,

Speed_Increment: Slow_Speed, Speed_Decrement: Half_Speed,

Speed_Decrement: Slow_Speed, Speed_Decrement: DeadSlow_Speed,

Engine_Stop: Engine_Stop, Engine_Reversion: Engine_ Reversion.

Obviously, some other actions are absurd, for example, *Speed_Decrement: Full_Speed*

(3) Magnitude of simultaneous alteration of course and speed. Actions of this kind are combinations of (1) and (2). Detailed format is: *Action: C_level—S_level*.

'Action' is a detailed combined action; '*C_level*' is level of alteration of course; '*S_level*' is level of alteration of speed. For example, *CAP_SD: Level_4—Slow_Speed* means the action is alter course to port and decrease her speed, and magnitude of course alteration is 40º and magnitude of speed alteration is to decrease her speed to slow speed.

<Action_Heuristic> is a set which contains actions including heuristic navigation information. And the actions are the ones which ships are unable to implement according to current situation.

<Action_Heuristic> = {< Unable_Give_Way >,
< Unable_Keep_CourseAndSpeed >,
< Unable_Turn_Left >, < Unable_Turn_Right >,
< Unable_Increase_Speed >,
< Unable_Decreasing_Speed >,
< Unable_Stop_Engine >, < Unable_Reverse_Engine >}

And the explanations of the heuristic actions are shown in Table 3-17.

Table 3-17 Explanation of Heuristic Actions

Heuristic Action	Explanation
Unable_Give_Way	Ship is unable to take give-way action because of some reason.
Unable_Keep_CourseAndSpeed	Ship is unable to keep her course and speed because of some reason.
Unable_Turn_Left	Ship is unable to alter her course towards left because of some reason.
Unable_Turn_Right	Ship is unable to alter her course towards right because of some reason.
Unable_Increase_Speed	Ship is unable to increase her speed because of some reason.

Unable_Decreasing_Speed	Ship is unable to decrease her speed because of some reason.
Unable_Stop_Engine	Ship is unable to stop her engine because of some reason.
Unable_Reverse_Engine	Ship is unable to reverse her engine because of some reason.

Now, a piece of knowledge of collision avoidance can be simply expressed by using the descriptors of states of ships and actions. For example, head-on situation can be described by two heuristic rules. And they are '*If distance from a target is 6 nm; during a period of time, its average relative bearing* $\theta \in [0^{o}, 6^{o}]$*; its aspect* $\alpha \in [-6,0]$*. Then own ship is involved in head-on situation with the target.*' And '*If conditions permit, own ship should alter her course towards starboard when she forms head-on with a target*'. The rules can be expressed as follows:

IF (P2 = < RBearing_Sector_1> AND

P3 = < Aspect_Head_On_DeadAhead_Starboard >

|< Aspect_Head_On_Port> AND

P4 = < Distance_Level_6>)

THEN (P1 = <Head_On_DeadAhead_Starboard> And

P5 = <Give_Way_State>)

IF (P1 = <Head_On_DeadAhead_Starboard> AND

P5 = < Give_Way_State > AND P6 = < Wide_Sea_Area > AND

P7= < Traffic_Excellent > AND P8 = < K_Level_2> AND

P9 = < Visibility_Good >)

THEN (Q = < Course_Alteration _Starboard >)

Obviously, practical decision-making of collision avoidance is far more complicated than the example, especially when own ship encounters multiple targets. In ESCAN, some rules propose possible avoiding actions. Some other rules veto, limit and modify these proposals so as to give more reasonable decision. Therefore, final decision is determined by rules of collision avoidance in the six modules of ESCAN all together.

In multi-ship encountering situation, the most common approach for dealing with collision avoidance is to select one target-ship as the primary target-ship to avoid. Moreover, in ESCAN, according to current situation and circumstance, it also provides the 'Scene Matching' function for searching a recorded scene for dealing with current situation [25]. If a proper scene is found, ESCAN will active it and show the detailed actions on USI. Obviously, these scenes should be strictly matched in case improper actions are provided so as to cause worse situation. *P13* (Multi-ship encountering situation descriptor) can be used to judge whether current situation is involved in a multi-ship encountering situation. In order to fulfill this function, a fact type for recording these multi-ship encountering cases (scenes) should be designed. And the fact type is designed as follows:

Multi_Target_Scene:: Scene_Serial_Number, Target_Number, Scene_Area,
Scene_Visibility, Other_Condition, Active_State

Here, *Scene_Serial_Number* is to record symbol name of a multi-ship encountering scene;

Target_Number is to record number of ships involved in the scene;

Scene_Area is to record this scene is happened in what kind of water area;

Scene_Visibility is to record the visibility when the scene happened;

Other_Condition is to record other special conditions when the scene happened, for example, obstacles existed on port side of own ship.

Active_State is to record whether the related scene is active. It is a Boolean variable, if it is TRUE, the scene is in activated state; otherwise, the scene is unactivated state.

In ESCAN, in order to agilely control these facts of scenes, a special approach is used to active and deactive the active states of the facts.

For example, *Scene_Serial_Number* of a scene is Scene001. Two target-ships are involved in the scene. And they can be named Scene001_T1 and Scene001_T2. Knowledge engineer will use other two rules to record the navigational information of the two target-ships for scene matching. And one matching flag of each target will be used to monitor whether information of a target is matched. Here, *Scene001_T1_Flag*, *Scene001_T2_Flag* are used to monitor matching states of the two target-ships of Scene001.

When value of *P13* is TRUE, ESCAN will detect whether *Target_Number* of scenes match current number of target-ships. If some scenes match, check whether the information of every target-ship of the scenes matches that of current target-ships. If one target-ship of a scene matches one of current ships, its matching flag should be TRUE, for example *Scene001_T1_Flag = TRUE*. When all matching flags of target-ships of one scene are all TRUE, the scene should be activated. But *Active_State* of a scene is TRUE is just one of the conditions that determine whether the scene is available for dealing with current situation. Other conditions are all should be considered. When all conditions are all satisfied, the scene is finally available and the related avoiding actions will be shown on USI. For example Scene001 happens in wide sea area, visibility is also good and no other conditions. Because *Target_Number* of a scene is matched is the first step of the process and the number is also implied in the number of matching flags of target-ships, it does not need to be matched again. And the matching process of Scene001 can be shown in Fig.3-7.

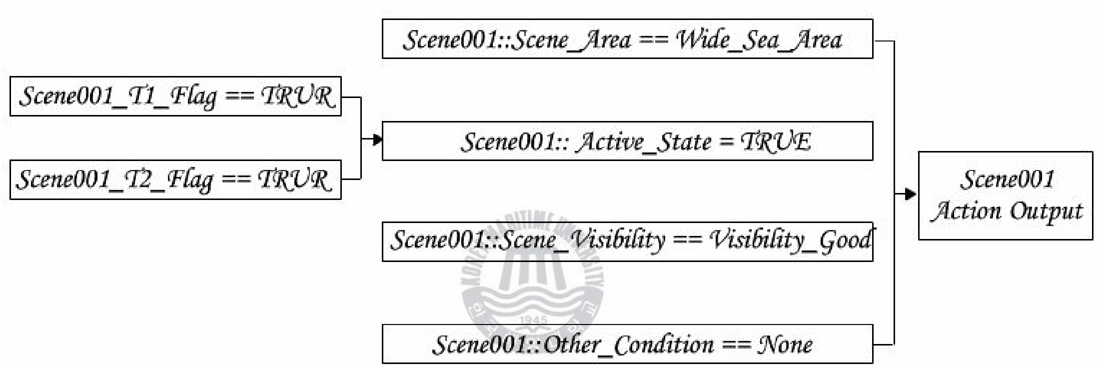


Fig.3-7 Scene001 Matching Diagram

If during the process of scene matching, number of target-ships changes, all matching flags should be reset. For example, if another target-ship appears during the matching process of Scene001, the process must be terminated and its matching flags also should be reset to be FALSE. That is to say, *Scene001_T1_Flag, Scene001_T2_Flag* and *Active_State* are all reset to be FALSE. Similarly, during the process, if a value of a target-ship (for example, relative bearing) changes so fast as to be off the related matching area of that value, the condition of the target no longer satisfies the scene, and the process also must be terminated and the matching flags of the scene must be reset.

Such design has some advantages as follows:

(1) It is not necessary to check all scenes all the time. For example, if there are two target-ships in the vicinity of own ship, only the scenes involving two target-ships should be checked.

(2) Strict match. If a scene is matched and available for dealing with current situation, not only all information of target-ships of it but also other all conditions of it need to match current situation. Actions of a specific scene are only reasonable in the restricted conditions of it. The same actions may be dangerous in other conditions. So the scenes must be strictly matched in case improper actions are suggested to navigators.

In addition, scenes also can be displayed by figures on USI in order to be browsed in an intuitionistic way. Users can conveniently select proper scenes for reference.

3.3.5 Management of Knowledge Base

Generally speaking, management of KB is to organize, manage, maintain and control knowledge in KB and provide users with approaches of operating knowledge and administrators. But knowledge of collision avoidance is very complicated, and it is hard to add rules which can satisfy the requirements of system by using simple deductions. Therefore, maintenance of KB is hard to be implemented by users. Tasks of maintenance and upgrade of KB are still undertaken by knowledge engineers.

System provides two levels of access authorization as follows:

Administrators have advanced access authorization. In addition to querying, searching and browsing knowledge in KB, they also can add, modify, delete knowledge, and modify, recompose, extend modules in KB.

Users have common access authorization. They can only query, search and browse knowledge in KB.

3.4 Design of Inference Engine

3.4.1 Induction of Inference Engine

When people analyze all kinds of knowledge and make comprehensive decision-making, they usually use the known facts and knowledge to find out implied facts, and then induce new ones. This process is called inference. Simply speaking, inference is a process to acquire a consequent from some known facts according to some certain rules. In an expert system, the task of inference is implemented by inference engine. That is to say, inference engine is the realization of inference in computer. It is an indispensable part in an expert system and has two aspects such as inference and control. And the primary task of inference engine is to infer a most appropriate decision by using the knowledge in KB and some control strategies of inference according to all known conditions.

In addition to having a lot of expertise, and what's more, experts can reasonably select and effectively utilize the knowledge to efficiently deal with complex problems. The task of knowledge-based inference is to select and utilize proper knowledge to solve complex problems. A pattern of utilizing knowledge is called an inference approach. Approaches of selecting knowledge are called control strategies of inference and they directly determine the effect and efficiency of inference.

There are many ways of think implied in human intelligent activities. Therefore, as a simulation of human intelligence, AI (artificial intelligence) also has many ways of inference. Classical logic is the foundation of the traditional inference technologies. Deduction inference is to infer consequent according to a group of known facts and some certain system of theories. It is one of the most commonly used methods of drawing inferences and has been used since ancient times to determine the validity of an argument. A number of other types of inferences are sometimes used with expert systems. Although these methods are not as general purpose as deduction, they are very useful, such as analogy, abduction, nonmonotonic reasoning and so on. Deduction inference can be easily implemented by using production rules. So it is used in ESCAN. It contains forward inference, backward inference and mixed inference.

Forward inference should be used in ESCAN because decision-making of collision avoidance can not be determined aforehand. However, the determined avoiding plans may be more than one. It is necessary to evaluate these plans so as to acquire the most appropriate one. And this task can be implemented by backward inference well. Considering these points, mixed inference which combines forward inference and backward inference is used in ESCAN. That is to say, firstly, ESCAN uses forward inference to acquire a set of plans of collision avoidance. And then it uses backward inference to evaluate these plans for acquiring the most appropriate one.

3.4.2 Inference Process of ESCAN

Inference is the act or process of deriving logical conclusions from premises known or assumed to be true. Considering ESCAN should be fast, accurate and efficient and a lot of practical navigation experience, a new inference process of collision avoidance is introduced. By using this inference process and the rules in KB and facts in FB, IE can infer the most appropriate plan of collision avoidance. As shown in Fig.3-8, the inference process (hereafter 'IP') can be explained as follows:

In this paper, the part of ESCAN programmed in VC++ is called 'Outer S/W' and that in CLIPS is called 'Inner S/W'.

Step 1: Outer S/W checks interface circuit for acquiring data from AIS receiver or radar/ARPA and judge whether a target exists or not. If no target exists, then own ship keeps ordinary navigation. Otherwise, Outer S/W informs Inner S/W and then IP enters *Step 2*.

Step 2: Inner S/W judge the encountering situation between own ship and the target, then IP enters *Step 3*.

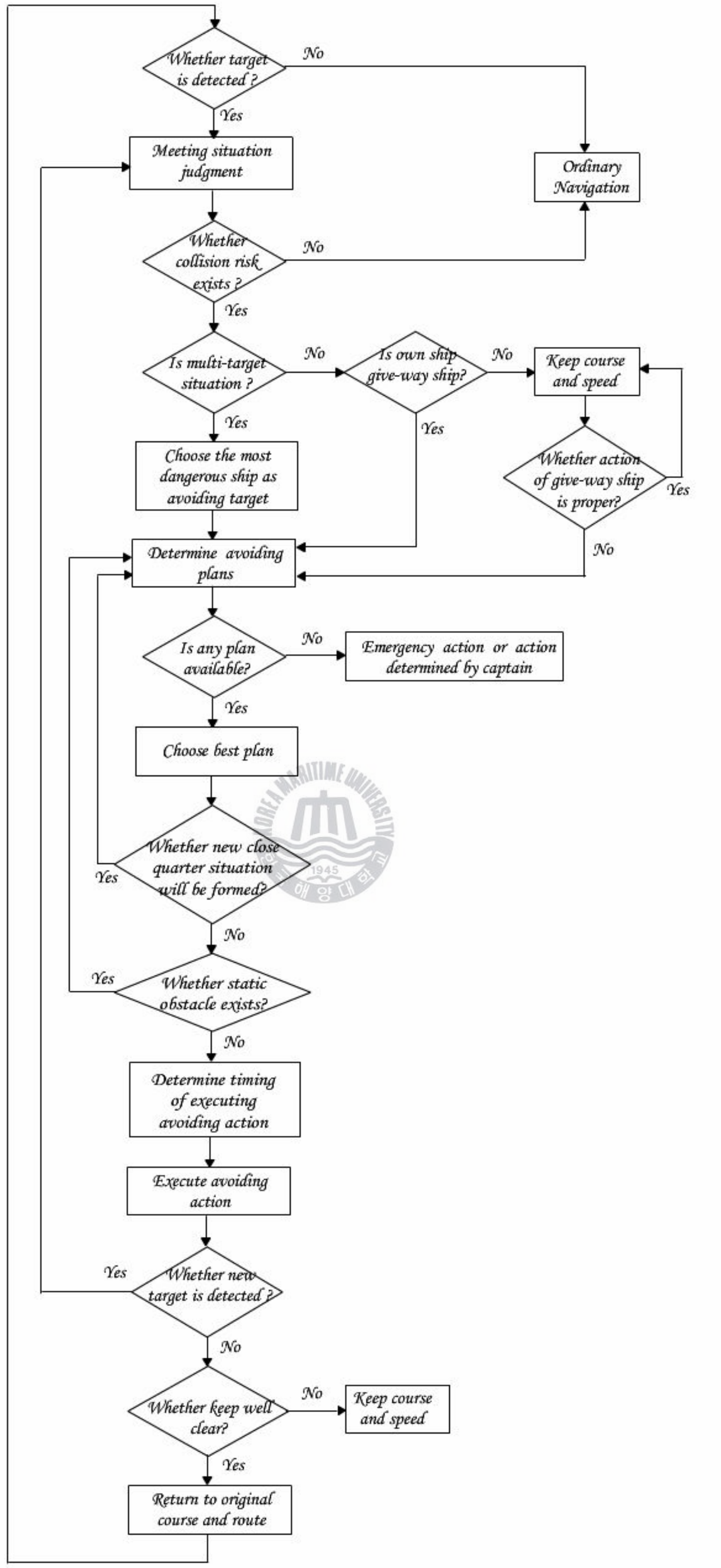


Fig.3-8 Flow Chart of Inference Process in ESCAN

Step 3: Inner S/W judges whether the collision risk of the target and own ship exists or not according to the result of *Step 2*. If collision risk does not exist, then own ship keeps ordinary navigation. Otherwise, IP enters *Step 4*.

Step 4: Inner S/W judge whether the current encountering situation is a multi-target encountering situation or not. If it is not, then IP enters *Step 5*. Otherwise, IP enters *Step 6*.

Step 5: Inner S/W judges whether own ship is the give-way ship or not. If own ship is, IP enters *Step 7*. Otherwise, own ship keeps her course and speed. Then Inner S/W checks whether the action of the give-way ship is proper or not. If it is proper, own ship continues keeping her course and speed. Otherwise, IP also enters *Step 7*.

Step 6: Inner S/W selects the most dangerous ship as the primary avoiding target of own ship. Then IP enters *Step 7*.

Step 7: Inner S/W makes avoiding action plans and informs Outer S/W to display these plans on USI. IP enters *Step 8*.

Step 8: Inner S/W judges whether there is an available plan or not. If no plan is available, Inner S/W informs Outer S/W to warn users. Own ship takes emergency action or the action determined by shipmaster. Otherwise, IP enters *Step 9*.

Step 9: Inner S/W selects a most appropriate plan and informs Outer S/W to display the plan on USI. Then IP enters *Step 10*.

Step 10: Inner S/W judges whether new close-quarter situation will be formed or not. If it will be formed, then IP goes back to *Step 7*. Otherwise, IP enters *Step 11*.

Step 11: Outer S/W detects whether any static obstacle is on the path of action plan. If a static obstacle exists Outer S/W informs Inner S/W, then IP goes back to *Step 7*. Otherwise, IP enters *Step 12*.

Step 12: Inner S/W decides the timing to take avoiding action and informs Outer S/W to display relevant information on USI. Then IP enters *Step 13*.

Step 13: Execute avoiding action. Inner S/W gives orders of avoiding action to autopilot or informs Outer S/W to display the orders on USI so that they can be manually implemented by users. Then IP enters *Step 14*.

Step 14: Outer S/W detects whether any new target exists or not. If new target does, Outer S/W informs Inner S/W and IP goes back to *Step 2*. Otherwise, IP enters *Step 15*.

Step 15: Inner S/W judges whether own ship has kept well clear off the target. If own ship hasn't, she continues keeping her course and speed. Otherwise, IP enters *Step 16*.

Step 16: Return to original course and route of own ship. Inner S/W gives relevant orders to autopilot or informs Outer S/W to display the orders so that they can be implemented manually by users. Then IP goes back to *Step 1* to continue next inference cycle.

In ESCAN, Inner S/W is in charge of inference and Outer S/W is in charge of receiving data from navigational equipment and users, displaying results of inferences of Inner S/W, and also providing several convenient functions, for example a function which uses graphic technology can simulate avoiding actions provided by Inner S/W.

During the inference process, deduction inference which can match production rules well is used. Mixed inference is one type of deduction inference and is used in the process. It is an inference approach that combines forward inference and backward inference. Forward inference is used to keep the inference process can be carried out smoothly from beginning to end. When available plans of collision avoidance are two or more, they should be evaluated to find out which one is the most appropriate and effective one by using backward chaining inference. And in next section, these inference approaches will be introduced.

3.4.3 Approaches of Deduction Inference

3.4.3.1 Forward Inference

Forward inference derives logical conclusions from data. It is a so-called fact-driven approach, that is to say, forward inference process is from IF to THEN. The inference process of this approach is as follows:

(1) According to original data contained in facts in FB, expert system searches the rules to find which can match them.

(2) If the rules are found, consequents of them will be saved into FB as intermediate results. And they can be continuously matched by other rules to acquire their consequents.

(3) The process will be terminated when final consequent is acquired.

The expert system language CLIPS which is used in ESCAN supports forward chaining inference. A group of multiple inferences that connects a problem with its solution is called a chain. A chain that is searched or traversed from a problem to its solution is called a forward chain. Another way of describing forward chaining is reasoning from facts to the conclusions that follow from the facts.

3.4.3.2 Backward Inference

Backward inference derives evidences from conclusions. It is a so-called goal-driven approach, that is to say, backward inference process is from THEN to IF. If the required proof of the hypothesis is found in FB, the inference is successful.

A chain that is traversed from a hypothesis back to the facts that support the hypothesis is a backward chain. Another way of describing a backward chain is in terms of a goal which can be accomplished by satisfying subgoals. CLIPS are designed for forward chaining and it can directly implement forward chaining inference. However, backward chaining can be emulated using forward chaining CLIPS rules.

3.4.3.3 Mixed Inference

Mixed inference is an inference approach which combines forward inference and backward inference and absorbs the advantages of them. And it contains two types: forward-backward inference and backward-forward inference. In ESCAN, the former is used. Firstly, inference engine uses forward inference to acquire a set of available plans of collision avoidance. Then it uses backward inference to evaluate the plans by using some criterions for acquiring a most appropriate one. Backward inference sets off from these possible plans to evidences which support them. Information of each plan such as *DCPA*, need to be calculated assuming the plan is chosen. By comparing the information and considering environment conditions and other related factors, a most appropriate plan of avoiding action can be chosen.

Considering a practical example, if own ship forms a starboard abeam crossing situation with a target-ship with high speed and is involved in collision risk with it, ESCAN will use forward inference and provide two avoiding plans for dealing with the situation. One of the plans is to substantially alter course of own ship to port side, and the other one is to reduce speed of own ship to dead slow speed and pass the target-ship astern. Then ESCAN uses backward inference to evaluate the plans and find out which one is better. Because speed of the target-ship is high, *DCPA* of latter plan is bigger, that is to say, own ship should reduce her speed to dead slow speed and wait to pass the target-ship astern. From this, we can see that mixed inference is more agile, good for improving the efficiency of ESCAN and can adapt to the specialties of expert system for collision avoidance.

3.4.4 Pattern-Matching Algorithm

The individual condition of production rule is called a conditional element or a pattern. The process of matching facts to pattern is called pattern-matching. Inference engine is the mechanism which automatically matches patterns against the current facts and determines which rules are applicable. In an expert system, efficiency of the pattern-matching algorithm concerns efficiency of whole expert system. In order to reach a satisfied pattern-matching efficiency, rule-based language CLIPS uses a very efficient algorithm for matching facts against the patterns in rules to determine which rules have had their conditions satisfied. This algorithm is called the Rete Pattern-Matching Algorithm.

In rule-based system, the matching process takes place repeatedly. Normally the fact list will be modified during each cycle of execution. New facts may be added to the fact list or old facts may be removed from it. These changes may cause previously unsatisfied patterns to be satisfied or vice versa. During each cycle, as facts are added and removed the set of rules satisfied must be maintained and updated. One method of matching is to have the inference engine check each rule to direct the search for facts after each cycle of execution provides a simple and straightforward technique for solving this problem. But the primary disadvantage of such an approach is that it can be very slow. And this obviously is unacceptable by an applied expert system.

Most rule-based expert system exhibit a property called temporal redundancy. Typically, the actions of a rule will only change a few facts in the fact list. That is, the facts in the expert system change slowly over time. Each cycle of execution may see only a small percentage of facts either added or removed and so only a small percentage of rules are typically affected by the changes in the fact list. Thus, having the rules drive the search for needed facts requires a lot of unnecessary computations, since most of the rules are likely to find the same facts in the current cycle as were found in the last cycle. The inefficiency of this approach is shown in Fig.3-9. The grey area represents the changes that have been made to the fact list.

Not only facts added by Outer S/W, but facts added or removed by executed rules can cause the changes. Unnecessary redundant recomputation could be avoided by remembering what has already been matched from cycle to cycle and then computing only the changes necessary for the newly added or newly removed facts, ass shown in Fig.3-10. The rules remain static and the facts change, so the facts should find the rules, and not the other way around.

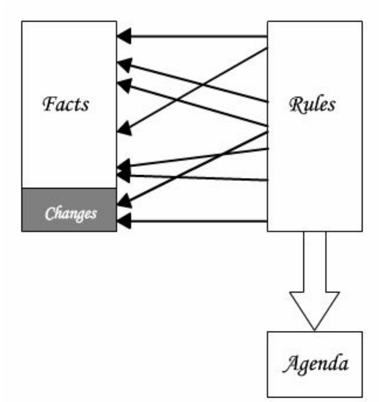


Fig.3-9 Rules Search for Facts in Ordinary Algorithm

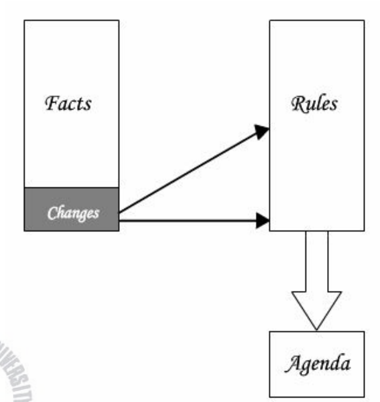


Fig.3-10 Facts Searching for Rules In Rete Algorithm

The Rete Pattern-Matching Algorithm is designed to take advantage of the temporal redundancy exhibited by rule-based expert systems. It does so by saving the state of matching process from cycle to cycle and recomputing the changes in this state only for the changes that occur in the fact list. That is, if a set of patterns finds two of three required facts in one cycle, it is not necessary for a check to be made in the next cycle for the two facts that have already been found – only the third fact is of interest. The state of the matching process is updated only as facts are added and removed. If the number of facts and removed is small compared to the total number of facts and patterns, the process of matching will proceed quickly. The algorithm also improves the efficiency of rule-based systems by taking advantage of structural similarity in the rules. Structural similarity refers to the fact that many rules often contain similar patterns or groups of patterns. The algorithm uses this feature to increase efficiency by pooling common components so they don't have to be computed more than once.

3.4.5 Conflict Resolution

During inference process, the known facts in FB continuously match rules in KB, and several possible situations may happen as follows:

(1) The known facts match no rules.

(2) The known facts match a single rule.

(3) The known facts match more than one rule, or different known facts or different groups of the known facts match a single rule, or different known facts or groups of known facts match different rules.

In ESCAN, during inference process, if situation (3) happens, that is to say, if antecedents of different production rules match same known facts (N: 1), or antecedent of a single production rule match different groups of known facts (1: N), or both of the two situations happen simultaneously (N: M), conflict happens. Simply speaking, if more than one rule is applicable, conflict happens. And when conflict happens, the inference engine uses a conflict resolution strategy to select which rule should have its actions executed. The actions of the selected rule are executed (which may affect the list of applicable rules) and then the inference engine selects another rule and executes its actions. This process continues until no applicable rules remain. In ESCAN, depth strategy is used. This strategy allows newly activated rules are place above all rules of the same salience in agenda.

Also CLIPS provides a technique for controlling the execution of rules: dynamic salience. The salience rule property allows the user to assign a priority to a rule. The agenda is the list of all rules which have their conditions satisfied (and have not yet been executed). Each module has its own agenda. Normally the agenda acts similar to a stack (the top rule on the agenda is the first one to be executed). Salience allows more important rules to stay at the top of the agenda, regardless of what time the rules are added. All rules of lower salience are placed below all rules of higher salience on the agenda. And newly activated rules are placed above all rules of lower salience and below all rules of higher salience. Salience is set using a numeric value ranging from the smallest value of -10,000 to the highest of 10,000. If a rule has no salience explicitly assigned by the programmer, CLIPS assumes a salience of zero. Therefore, in ESCAN, some rules for dealing with emergencies can be given higher salience so as to ensure that these rules can be activated and executed properly when emergencies happen.

3.5 Design of User-System Interface

User-system interface is the mechanism for implementing the communication between users and ESCAN. USI of ESCAN is developed by Visual C++ and will be detailedly introduced in Chapter 4.

Chapter 4 Implementation of ESCAN

4.1 Principles for Developing Expert Systems

It is complex to develop an expert system. Also, it may be developed by various approaches. So far, there is no standard procedure for developing expert system. To develop such system usually means coding, testing and modifying over and over again. As concerning the development of ESCAN, the following principles are complied with.

(1) Determining the proper field of research and relevant questions.

Expert system is a program which can deal with the problems of specific filed and provide expert-level solutions. The performance level of an expert system lies on the extent of abundance of knowledge in knowledge base of it. So in order to develop an expert system, according to practical requirements, determining proper field of research and relevant questions is the first crucial issue to be solved. And the following aspects are considered before planning of ESCAN.

(a) Purpose of development of ESCAN. The purpose is to reduce the occurrences of collisions or dangerous situations between ships at sea.

(b) Use of ESCAN. It should be able to provide reliable and reasonable decision-making of collision avoidance for dealing with current situation.

(c) Users of ESCAN. Ship pilots, shipmaster, and other navigators who use

ESCAN for navigation.

(d) Knowledge used in ESCAN. It is collected from COLREGS, comments and explanations of it, expertise of navigation experts and practical cases of collision avoidance with good seamanship.

(e) The intelligent level that ESCAN should have. ESCAN should be able to provide expert-level suggestions of collision avoidance for dealing with ordinary and complicated situations.

(f) Functions which ESCAN should have. ESCAN should be able to display navigational information of own ship and target-ships in the vicinity of her; to provide tips of navigation or actions of collision avoidance according to current situation; to predict and simulate the development of current situation.

(2) Planning and design of ESCAN

During the phase of planning ESCAN, the primary work is to carry out integrated design and functional design of it. Moreover, this step can also be called conceptualization design. It requires that the all kinds of conceptions, entities and their interrelationship for solving the problems of collision avoidance should be briefly described. Also, apparent functions which ESCAN should have are required to be determined in the step. Detailed tasks of the step are as follows:

(a) The first task is to determine the basic functions of ESCAN, to divide functional modules of it, to determine the functions of every module and the interrelationship of them, to draw the flow chart of overall structure and to write design specification of it.

(b) The second task is to determine the flow of inference and control, that is to say, to use flow chart of inference and flow chart of control to express the direct and indirect paths of inference and approaches of control between known facts and goals of inferences.

(c) The third task is to determine the layout of USI, relevant menus of functions and so on.

(3) Acquiring knowledge of collision avoidance

Knowledge acquirement is the most important step and is the starting point of developing expert system. Also, it is the hardest and fussiest step. In order to elicit domain knowledge and experience from navigation experts and represent them using some specific forms which can be identified and processed by computer, developers of system should collect a great lot of knowledge and practical instances from materials of collision avoidance, and communicate with navigation experts time after time. And then they should carefully analyze and summarize the knowledge, and conclude the principles and approaches for dealing with collision avoidance.

4.2 Functional Description of ESCAN

Decision-making of experts is a complicated activity of brain. In order to enable ESCAN to have the similar ability of solving problems which human navigation expert has, developers should try to add more useful knowledge and design more convenient and intelligent functions in ESCAN. Along with use of AIS technology, inference can be carried out by using more abundant and reliable knowledge and more new intelligent functions can also be developed. Function description of ESCAN is as follows:

(1) It is able to receive static and dynamic navigational data of own ship and target-ships from navigation equipment including AIS receiver and GPS receivers and so on, and transform the data into CLIPS-format facts which can be used by Inference Engine of ESCAN.

(2) It is able to judge encountering situations between own ship and target-ships and provide appropriate plans of collision avoidance.

(3) It is able to predict movement trends of target-ships and simulate them for observing the development of current situation.

(4) It is able to provide users with a function which uses graphic representation to browse multi-ship encountering practical cases.

(5) It is able to record the information provided by it to file. Also it is able to record current traffic situation to file and redisplay such situations by reading recorded files.

4.3 Computing Formulas Used in ESCAN

When a target-ship is detected and targeted by radar, radar/ARPA can provide some information of it which includes distance from the target, bearing, relative speed and *DCPA, TCPA* of it [7]. But some information of a target such as its position information (latitude and longitude) needs to be calculated for acquiring. And some other information for example heading of a target is usually observed and acquired by using telescope before use of AIS. With use of AIS technique, these problems are solved quite well. AIS can provide not only dynamic but also real-time data of target-ships [10]. These data are very important to navigators for judging current situation and further making appropriate decision of collision avoidance. However, it doesn't mean AIS can provide all necessary data because it just can provide the information from relevant equipment of target-ships. Information for describing relationship between own ship and target-ships needs to be calculated.

4.3.1 Formulas for Calculating Information of Relationship between Own Ship and One Target-ship

In this paper, geographical coordinates of own ship received from GPS receiver are set to be (*LatiO ,LongiO*); that of a target-ship received from AIS receiver are set to be (*LatiT, LongiT*). Because collision avoidance always happens in close areas of own ship, geographical coordinates can be approximately used as rectangular coordinates. Latitude and longitude can be thought as X-axis and Y-axis respectively, and relevant rectangular coordinates of own ship are set to be (X_O, Y_O) and that of target-ship are set to be (X_T, Y_T). True speed of own ship received from GPS is set to be V_O(knot), and course C_O(°) ; True speed of target-ship received from AIS is set to be V_T(knot) and course C_T(°). Detailed formulas are as follows:

(1) Formulas for calculating distance from a target-ship and bearing of it:

(a) Distance from a target-ship R

$$R = \sqrt{(X_T - X_O)^2 + (Y_T - Y_O)^2} \tag{4-1}$$

(b) True bearing of a target-ship to own ship

$$\theta = act\tan\frac{X_T - X_O}{Y_T - Y_O} + \beta \qquad \text{here,} \quad \beta = \begin{cases} 0^\circ, X_T \geq X_O, Y_T \geq Y_O \\ 180^\circ, Y_T < Y_O \\ 360^\circ, X_T < X_O, Y_T \geq T_O \end{cases} \tag{4-2}$$

(c) True bearing of own-ship to a target-ship

$$\theta_T = act\tan\frac{X_O - X_T}{Y_O - Y_T} + \beta_T, \quad \text{here,} \quad \beta_T = \begin{cases} 0^\circ, X_O \geq X_T, Y_O \geq Y_T \\ 180^\circ, Y_O < Y_T \\ 360^\circ, X_O < X_T, Y_O \geq T_T \end{cases} \tag{4-3}$$

(2) Formulas for calculating relevant indices of a target-ship

(a) Relative speed V_R

Components in the directions of latitude and longitude of V_O are set to be V_{OX} and V_{OY}, and that of V_T are set to be V_{TX} and V_{TY}. The formulas are as follows:

$$\begin{cases} V_{OX} = V_O \cdot \sin C_O \\ V_{OY} = V_O \cdot \cos C_O \end{cases} \tag{4-4}$$

$$\begin{cases} V_{TX} = V_T \cdot \sin C_T \\ V_{TY} = V_T \cdot \cos C_T \end{cases} \tag{4-5}$$

Components in the directions of latitude and longitude of V_R are set to be V_{RX} and V_{RY}, and they can be calculated by the formula as follows:

$$\begin{cases} V_{RX} = V_{TX} - V_{OX} \\ V_{RY} = V_{TY} - V_{OY} \end{cases} \tag{4-6}$$

So the relative speed V_R and course C_R are as follows:

$$V_R = \sqrt{V_{RX}^2 + V_{RY}^2} \tag{4-7}$$

$$C_R = \arctan\frac{V_{RX}}{V_{RY}} + C_M \text{ , here } C_M = \begin{cases} 0^\circ, V_{RX} \geq 0, V_{\mathrm{RY}} \geq 0 \\ 180^\circ, V_{RY} < 0 \\ 360^\circ, V_{RX} < 0, V_{RY} \geq 0 \end{cases} \tag{4-8}$$

(b) Relative bearing of a target-ship to own ship θ_r

$$\begin{cases} \theta_r = \theta - C_O \\ \theta_r = \theta_r + 360^\circ, when\ \ \theta_r < 0^\circ \end{cases} \tag{4-9}$$

(c) *DCPA*

$$\mathrm{DCPA} = R \cdot \sin\left|C_{\mathrm{R}} - (\theta + 180)\right| \tag{4-10}$$

(d) *TCPA*

$$\mathrm{TCPA} = \frac{R \cdot \cos\left|C_{\mathrm{R}} - (\theta + 180)\right|}{\mathrm{V_R}} \tag{4-11}$$

AIS can directly provide much static information of target-ship including name, call sign, length, breadth and type of it. And it also can provide much real-time and dynamic information of movement of target-ship. These data are greatly helpful to navigators for making early warning judgments. Based on the data, much important information including the above information can be calculated.

4.3.2 Formulas for Calculating Information of Relationship between Two Target-ships

In multi-ship collision avoidance situations, own ship needs to know encountering situations with every target-ship and encountering situations of target-ships each other, and then predict possible actions which target-ships may take. Therefore, information of relationship of target-ships each other should be calculated. Formulas for calculating the information between *Target A* and *Target B* are given as follows:

Position of *Target-ship A* is set to be (X_A, Y_A), speed and course of it are set to be V_A and C_A ; that of *Target-ship B* are set to be (X_B, Y_B), V_B and C_B respectively.

(a) Distance between *Target A* and *Target B* R_{BA}

$$R_{BA} = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2} \tag{4-12}$$

(b) Relative speed of *Target B* to *Target A* $V_{R\text{-}BA}$

Components in the directions of latitude and longitude of $V_{R\text{-}A}$ are set to be V_{AX} and V_{AY}, and relevant components of $V_{R\text{-}B}$ are set to be V_{BX} and V_{BY}. The formulas are as follows:

$$\begin{cases} V_{AX} = V_A \cdot \sin C_A \\ V_{AY} = V_A \cdot \cos C_A \end{cases} \tag{4-13}$$

$$\begin{cases} V_{BX} = V_B \cdot \sin C_B \\ V_{BY} = V_B \cdot \cos C_B \end{cases} \tag{4-14}$$

Components in the directions of latitude and longitude of $V_{R\text{-}BA}$ are set to be $V_{R\text{-}BAX}$ and $V_{R\text{-}BAY}$ and they can be calculated by the formula as follows:

$$\begin{cases} V_{R\text{-}BAX} = V_{BX} - V_{AX} \\ V_{R-BAY} = V_{BY} - V_{AY} \end{cases} \tag{4-15}$$

So the relative speed of *Target B* to *Target A* $V_{R\text{-}BA}$ and course $C_{R\text{-}BA}$ are as follows:

$$V_{R-BA} = \sqrt{V_{R\text{-}BAX}^2 + V_{R-BAY}^2} \tag{4-16}$$

$$C_{R-BA} = \arctan\frac{V_{R-BAX}}{V_{R-BAY}} + C_{M-BA}, \quad \text{here}$$

$$C_{M-\mathrm{BA}} = \begin{cases} 0^\circ, V_{R-\mathrm{BA}X} \ge 0, V_{\mathrm{R\text{-}BAY}} \ge 0 \\ 180^\circ, V_{R-\mathrm{BA}Y} < 0 \\ 360^\circ, V_{R-\mathrm{BA}X} < 0, V_{R-\mathrm{BA}Y} \ge 0 \end{cases} \tag{4-17}$$

(c) True bearing of *Target B* to *Target A*

$$\theta_{\mathrm{BA}} = \arctan\frac{X_B - X_A}{Y_B - Y_A} + \beta_{\mathrm{BA}} \quad \text{here,} \quad \beta_{BA} = \begin{cases} 0^\circ, X_B \ge X_A, Y_B \ge Y_A \\ 180^\circ, Y_B < Y_A \\ 360^\circ, X_B < X_A, Y_B \ge T_A \end{cases} \tag{4-18}$$

(b) Relative bearing of *Target B* observed from *Target A*

$$\begin{cases} \theta_{r-\mathrm{BA}} = \theta_{\mathrm{BA}} - C_A \\ \theta_{r-\mathrm{BA}} = \theta_{r-\mathrm{BA}} + 360^\circ, when\ \ \theta_{r-\mathrm{BA}} < 0^\circ \end{cases} \tag{4-19}$$

(c) *DCPA $_{BA}$* between *Target A* and *Target B*

$$\mathrm{DCPA}_{\mathrm{BA}} = R_{BA} \cdot \sin\left|C_{R-BA} - (\theta_{BA} + 180^\circ)\right| \tag{4-20}$$

(d) *TCPA $_{BA}$* between *Target A* and *Target B*

$$\mathrm{TCPA}_{\mathrm{BA}} = \frac{R_{BA} \cdot \cos\left|C_{R-BA} - (\theta_{BA} + 180^\circ)\right|}{\mathrm{V_{R\text{-}BA}}} \tag{4-21}$$

4.3.3 Formulas for Calculating Position of One Target-ship by Using Data from Radar

Radar can not provide latitude and longitude of targets, but these values can be calculated by using relevant information. If distance from a target is *R*, and its true bearing is *θ*, and geographical coordinates of own ship received from GPS receiver are (*LatiO* ,*LongiO*), radius of earth is R_E, then geographical coordinates of the target-ship are set to be (*LatiT, LongiT*) and they can be calculated as follows:

$$LatiT = LatiO + 180^{\circ} \frac{R \cos \theta}{\pi R_E} \tag{4-22}$$

$$LongiT = LongiO + 180^{\circ} \frac{R \sin \theta}{\pi R_E \cos(LatiO)} \tag{4-23}$$

4.4 Approach for Judging Whether Ships Have Kept Well Clear off Each Other

Criterion for judging whether a given-way ship has kept well clear off the relative stand-on ship is to judge whether she still can pass the stand-on ship at a safe distance if she takes her course for some purpose (return original course or avoid other ships and so on) after the stand-on ship passes *CPA*. In ESCAN, a *preset—test* approach is used. When own ship is a given-way ship, the action of returning to original course is the default action which she will take after the stand-on ship passes *CPA*. If other actions are needed to be taken after a target-ship passes *CPA*, users should preset them into ESCAN. Then when target-ship passes *CPA*, ESCAN will start to calculate the new *DCPA* which will be formed assuming the specific preset action is taken. ESCAN will continue test the new *DCPA* and terminate the testing procedure when the new *DCPA* is bigger than the minimum safe passing distance. And then ESCAN will inform navigators that they can execute the preset action or give relevant orders to autopilot. During the process of testing, own ship should keep her course.

Similarly, when own ship is a stand-on ship, users also can preset some specific action other than keeping her course and speed. And when target-ship passes *CPA*, ESCAN will start to test whether the preset actions will cause new close-quarters situation. When the new *DCPA* is satisfying, ESCAN will inform navigators to execute the actions or give orders to autopilot.

ESCAN also provides a function for predicting *DCPA*. Based on current situation, the function can predict value of *DCPA* of a target at a certain period of time later. For example, when a target-ship passes *CPA*, if own ship plans to return original course 5 minutes later, navigators can use the function to check whether the value of *DCPA* at 5 minutes later is satisfying so as to keep well clear off the target-ship.

4.5 Approach for Determining Magnitude of Avoiding Action

In ESCAN, knowledge engineers have already given a certain value for every specific encountering situation. According to COLREGS, avoiding actions should be large enough to be readily apparent to another ship observing visually or by radar, so usually magnitude of alteration of courser is not smaller than 30º in ESCAN. In some situations, in order to reach safe passing distance, ESCAN will adjust the magnitude of the relevant actions. If avoiding action is alteration of course, ESCAN will add 10º every time until safe passing distance is reached. If it is decrement of speed, ESCAN will decrease speed to a lower level until safe passing distance is reached.

4.6 Software for Developing ESCAN

4.6.1 Two Types of Software

CLIPS is a public domain software tool for building expert systems and has been introduced in section 1.3. It is probably the most widely used expert system tool because it is fast, efficient and free. However, it does not provide the technology for implementing convenient interfaces. Therefore, it is necessary to export itself to other language like Visual C++ for fulfill such job.

Microsoft Visual C++(often abbreviated as MSVC) is a commercial integrated development environment (IDE) product engineered by Microsoft. It has tools for developing and debugging C++ code. In it, programmers can program all kinds of powerful software by coding and designing convenient dialog boxes. It is one of the most popular programming tools.

For such purpose, Visual C++ 6.0 is used is to imbed CLIPS in ESCAN.

4.6.2 Embedding of CLIPS in Visual C++

Embedding CLIPS in Visual C++ is a good approach to develop ESCAN. In Visual C++, the program for data collection and information demonstration should be developed. On the other hand, the embedded CLIPS system should take charge of the task of inferences. When the navigational rules are required to be upgraded, programmers only need to rewrite the relevant rules rather than reprogram the whole program.

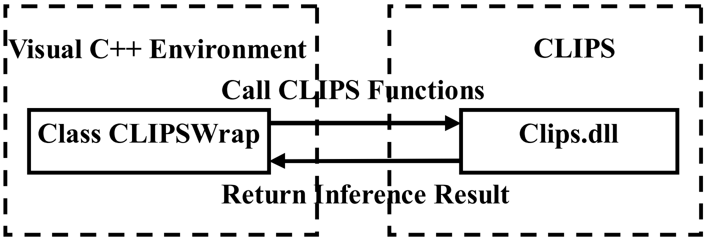


Fig.4-1 Embedding CLIPS into Visual C++

A dynamic link library (DLL) file named *clips.dll* is used to fulfill the embedding job. Moreover, a class named *CCLIPSWrap* can link *clips.dll* well. The class can call the main CLIPS functions in *clips.dll* easily and it follows the function-call style of C++ language. So programmers can utilize the member variables and member functions of the class to call the kernel functions of CLIPS through *clips.dll*. In this way, programmers can call CLIPS kernel functions in Visual C++ environment, so as to implement the embedded program by using CLIPS and Visual C++. The method can be simply described as Fig.4-1.

4.7 Building the Modules of Knowledge Base

KB in ESCAN is divided into 6 modules (as Fig. 3-4 shows) and relevant rules of each module are preserved and can only be used inside each module respectively unless they are exported to other modules. CLIPS supports module structure. A rule can be identified by using name of a module. For example a rule of Encountering Situation Judgment Module which is '*If distance from a target is 6 nm or less; during a period of time, its average relative bearing* $\theta \in [0^{o}, 6^{o}]$*; its aspect* $\alpha \in [-6,0]$*, then own ship becomes involved in head-on situation with the target.*'

can be defined in CLIPS format as follows:

```
(defrule JudgmentEncouteringSituation::state-decision-1
  (declare (salience 100))
  ?f1 <- (EncounteringStateDecision (TargetToDecision ?name))
  ?f2 <- (Target (target-name ?name)
          (Relative-Bearing ?Relative-Bearing)(Aspect ?Aspect))
  ?f3 <- (OwnShip (OwnShipState ?OwnShipState))
  (test   (and(or (and (>= ?Relative-Bearing 354)(<= ?Relative-Bearing 360))
            (and (>= ?Relative-Bearing 0)(<= ?Relative-Bearing 6)))
            (and (> ?Aspect -6)(< ?Aspect   6))))
 =>
 (retract ?f1)
 (modify ?f2 (EncounteringState 1))
 (modify ?f3 (OwnShipState 1)))
```

4.8 Layout of User-System Interface

4.8.1 Main User-System Interface

As Fig. 4-2 shows, Main USI consists of four parts such as Current Situation Display Area (top-left part), Information List Area (top-right part), Information of Own Ship Display Area (bottom-left part) and Target List Area (bottom-right part).

Current Situation Display Area is to clearly display current traffic situation in the vicinity of own ship. Own ship locates at origin point and targets locate according to their bearing respectively. ESCAN provides two modes to display current situation and they are True Mode and Relative Mode respectively. In this way, users can easily focus their mind on current traffic situation between own ship and target-ships without the influence of other information. Users also can save the current situation to a file as a record and can redisplay such situations by using the recorded files.

Information List Area is to display recommendations of avoiding actions or other suggestive information provided by ESCAN. Users can acquire recommendations, suggestions, instructions or warning information provided by ESCAN from this list. Moreover, users also can save the information to a file as a record.

Information of Own Ship Display Area is to display navigational information of own ship which is received from GPS receiver or Compass in real-time so that users can observe necessary information of own ship when they use ESCAN.

Target Information Display Area is to display navigational information of the detected targets in real-time. Once a target-ship is detected, ESCAN will keep observing it and display its information on this area until it is out of range. Users can acquire detailed information of target-ships from this area. Moreover, targets can be browsed by different types (detected, monitored and displayed).

On the main user-system interface, a system menu is also provided. Users can conveniently use this menu to call other interfaces or functions. And the menu is shown in Fig. 4-3.

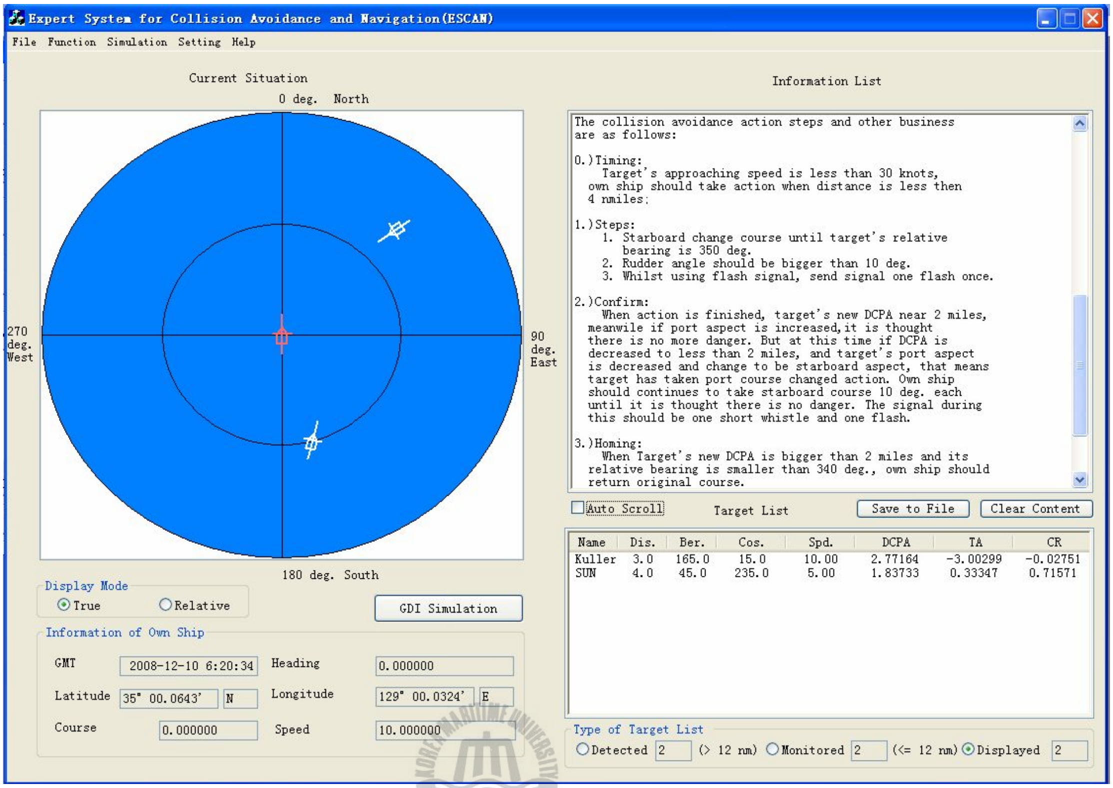


Fig.4-2 Main User System Interface of ESCAN

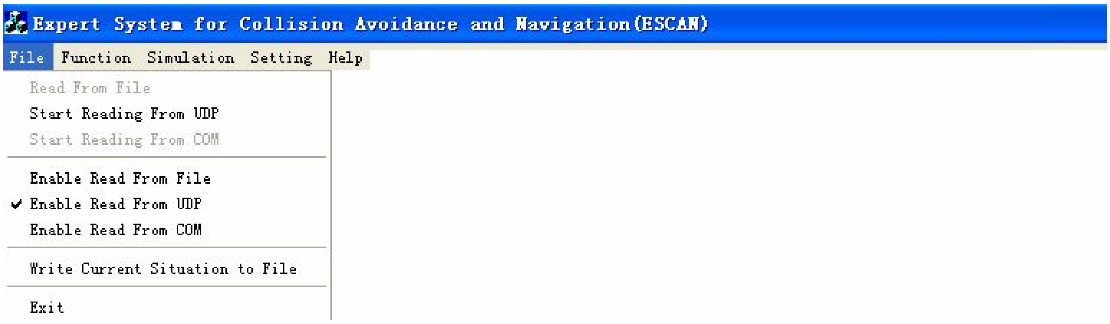


Fig.4-3 Menu of Main User System Interface of ESCAN

4.8.2 Other Interfaces

ESCAN also provides users with some other useful interfaces such as Simulation Dialog for simulation function, Safe Zone Calculation Dialog for acquiring safe zone of action and so on. And layout of these interfaces will be introduced together with their relevant functions later.

4.9 Practical Functions of ESCAN

4.9.1 Primary Function

Obviously, primary function of ESCAN is to provide recommendations, suggestions or instructions when own ship becomes involved in risk of collision with other target-ships or obstacles according to the information from AIS receivers and other navigational equipment.

When ESCAN receives information of targets, it will analyze it and then draw inferences for dealing with current situation. If own ship becomes involved in risk of collision, ESCAN will give recommendations and instructions for preventing own ship collide with other targets. Otherwise, ESCAN will give tips or suggestive messages for helping navigators to know current situation in the vicinity of own ship.

Table 4-1 Data of Own ship and a Target-ship

	Own Ship	Target-Ship
Distance(nm)	--	4.0
Bearing(°)	--	45
Course(°)	000	235
Speed(knot)	10	10

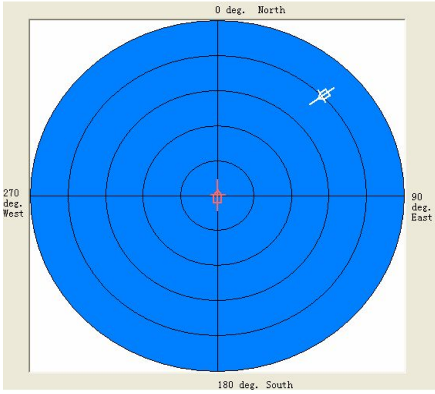
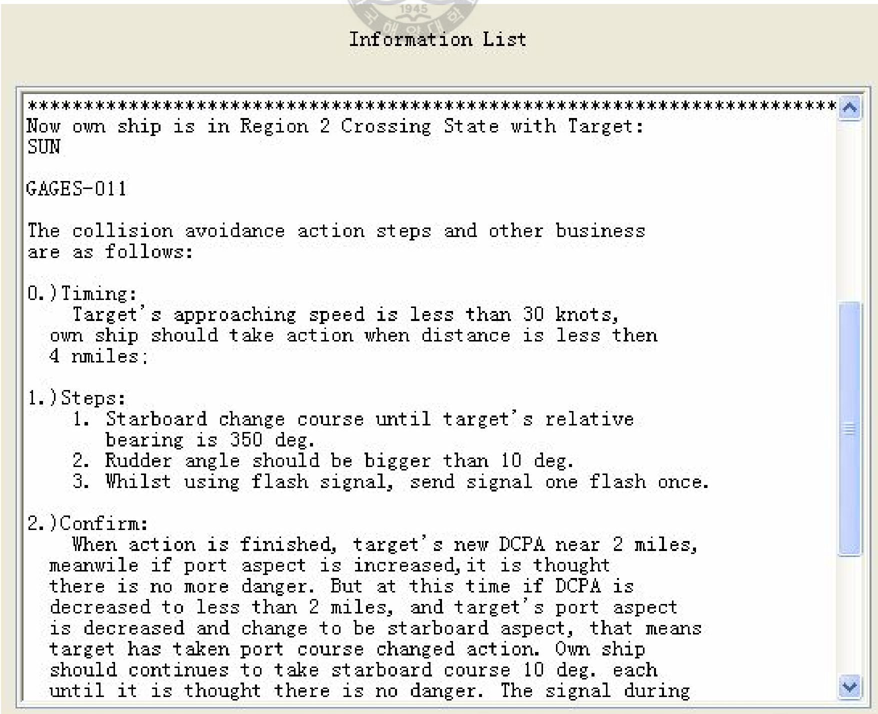


Fig.4-4 An Example of Crossing Situation

For example, own ship is involved in a starboard crossing situation with a target-ship as shown in Fig.4-4. Their related data are shown in Table 4-1. ESCAN gives a recommendation and display it in information list as shown in Fig.4-5. And the recommendation is that own ship should substantially take course towards starboard.



Information List

****
Now own ship is in Region 2 Crossing State with Target:
SUN

GAGES-011

The collision avoidance action steps and other business
are as follows:

0.)Timing:
Target's approaching speed is less than 30 knots,
own ship should take action when distance is less then
4 nmiles;

1.)Steps:
1. Starboard change course until target's relative
bearing is 350 deg.
2. Rudder angle should be bigger than 10 deg.
3. Whilst using flash signal, send signal one flash once.

2.)Confirm:
When action is finished, target's new DCPA near 2 miles,
meanwile if port aspect is increased,it is thought
there is no more danger. But at this time if DCPA is
decreased to less than 2 miles, and target's port aspect
is decreased and change to be starboard aspect, that means
target has taken port course changed action. Own ship
should continues to take starboard course 10 deg. each
until it is thought there is no danger. The signal during

Fig.4-5 Recommendation of ESCAN for Example of Crossing Situation

This is an example of dealing with single target encountering situation by using ESCAN. Dealing with multiple target-ships encountering situations by using ESCAN will be introduced in section 4.11.

4.9.2 Auxiliary Functions

4.9.2.1 Simulation Function

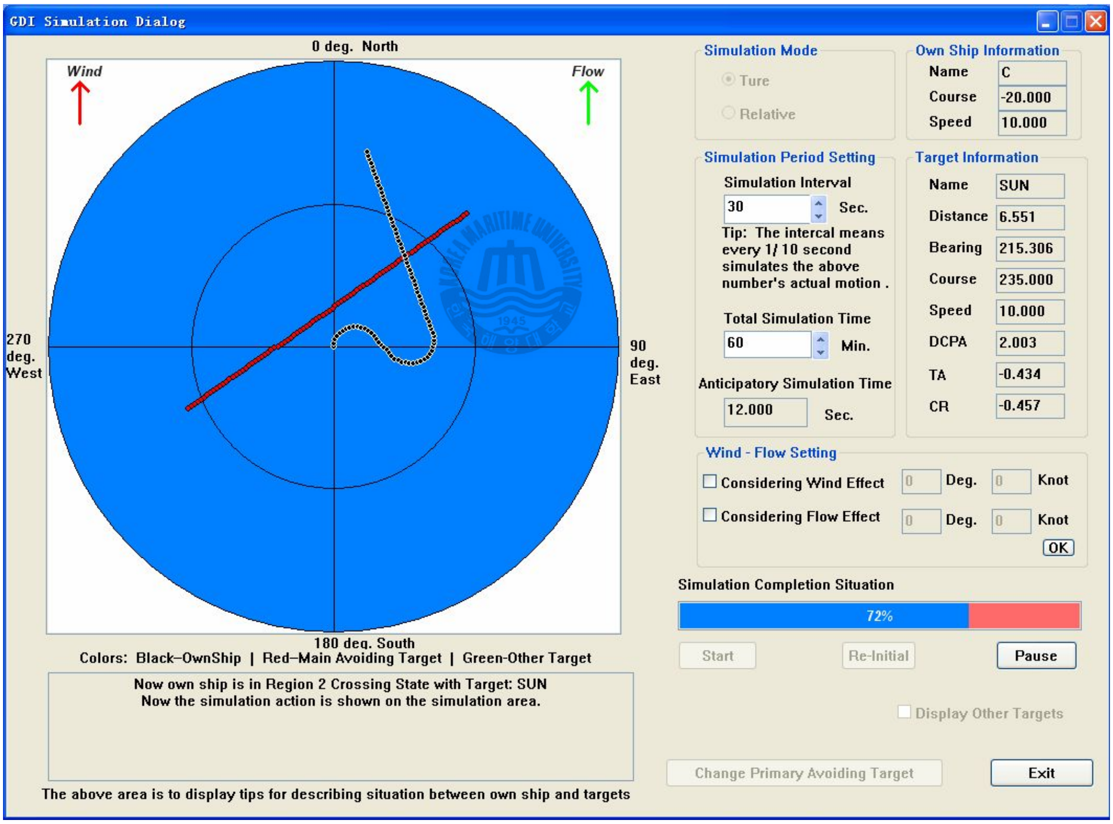


Fig.4-6 Simulation of Recommendation of ESCAN for an Example of Crossing Situation

Obviously, text recommendations as shown in Fig.4-5 are too bald. Moreover, users usually prefer to preview the effect of the recommendations before they actually execute them. In order to satisfy this requirement of users, ESCAN provides a function to simulate the process of the recommended avoiding actions by using GDI technology of VC++.

As shown in Fig.4-6, layout of simulation dialog box of ESCAN is displayed. It consists of several parts. The primary part is the simulation area (top-left part). And it is to display the simulation process of the avoiding actions assuming that reference frame is fixed and own ship moves from the origin. One concentric circle stands for one nm, that is to say, range of simulation area is 5 nm. Below simulation area is the tip area for displaying tips for describing the situation between own ship and target-ships. On right side of the dialog, uses can adjust parameters of simulation by using the options of simulation setting. Also, during the process of simulation, information of own ship and the primary target-ship to avoid can be observed on right side of the dialog. The influence of wind or flow can be considered if it can not be ignored. On bottom-right part, several buttons are provided. Users can use them to control the process of simulation. In Fig.4-6, avoiding action process of the recommendation shown in Fig.4-5 is simulated.

4.9.2.2 Safe Action Zone Calculation Function

As discussed in section 2.4.5, safe action zones can be acquired. ESCAN provides a function to calculate these zones. These zones are determined by threshold of collision risk.

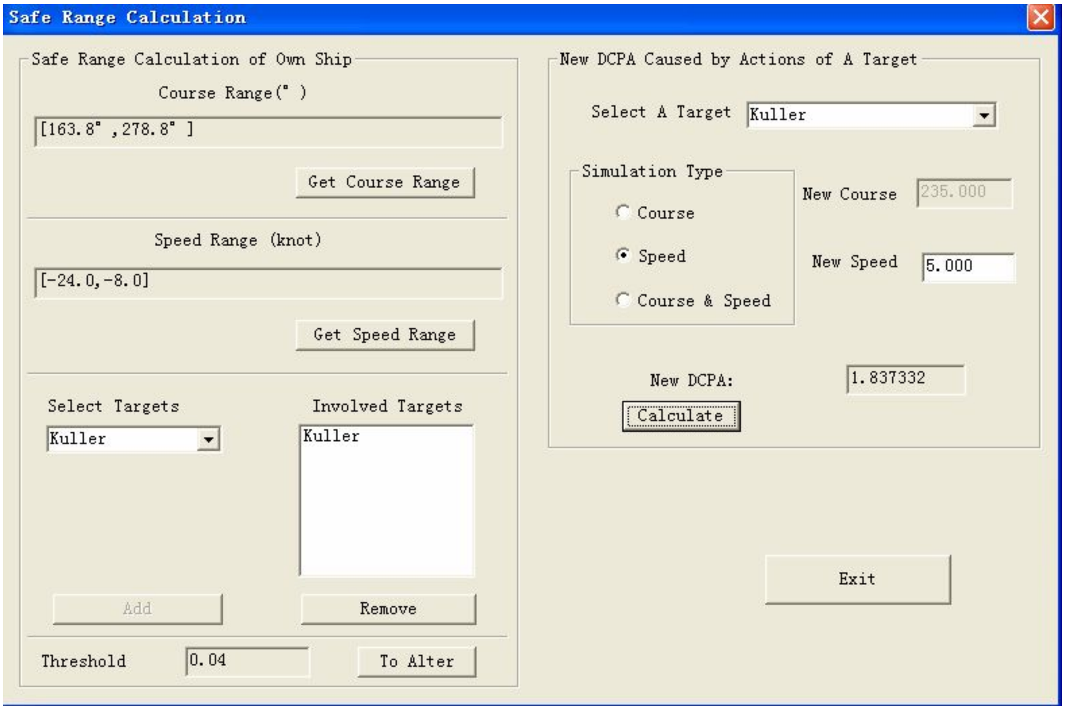


Fig.4-7 Safe Zone Calculation of the Example of Crossing Situation in Section 4.9.1

As shown in Fig.4-7, layout of safe zone calculation interface is displayed. Users can acquire the safe zone of course and safe zone of speed conveniently. Value of threshold of collision risk can be reset on the dialog. In ESCAN, the value of collision risk is set to be 0.04, safe zone of course of the example in section 4.9.1 is [163.8º, 278.8º], and safe zone of speed is [-24.0,-8.0] knot. ESCAN also provides a function to pre-calculate DCPA of a target-ship assuming that it takes a specific action. In Fig.4.6, if the target of the example decreases its speed to 5 knot, *DCPA* of it will increase from 1.202 to 1.837 nm. Safe zones are especially important in situations of multi-target collision avoidance and they are provided by ESCAN as a part of recommendation.

4.9.2.3 Data Browse Function

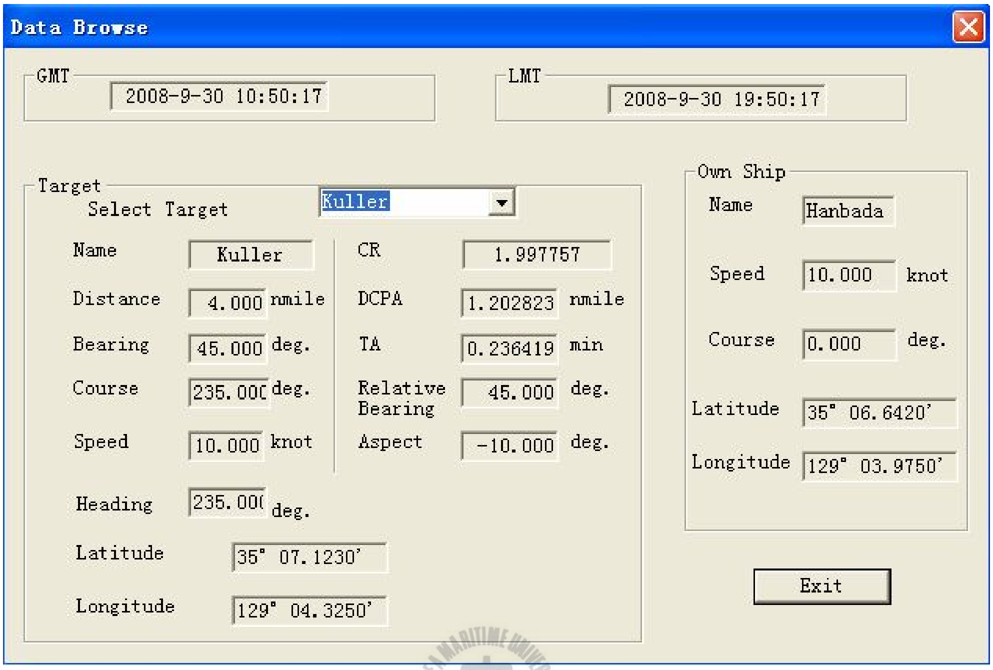


Fig.4-8 Data Browse Dialog Box of ESCAN

Although data of own ship and target-ships can be simply observed on Main USI, sometimes, users may want to observe more detailed data. ESCAN provides users with a dialog box for browsing detailed data of own ship and target-ships. As shown in Fig.4-8, more detailed data can be browsed on 'Data Browse' dialog box.

4.9.2.4 Ship Information Input and Modification Function

Sometime, users need to input data into ESCAN for practicing or simulating some specific situations. ESCAN provides two dialog boxes for receiving data input or modified by users. The ship information input dialog box is shown in

Fig.4-9 and the ship information modify dialog box is shown in Fig.4-10.

By using ship information input dialog, users can input navigational information of own ship. Moreover, users can input information of multiple targets. When users complete the process of inputting, the information of targets will be inserted into ESCAN together.

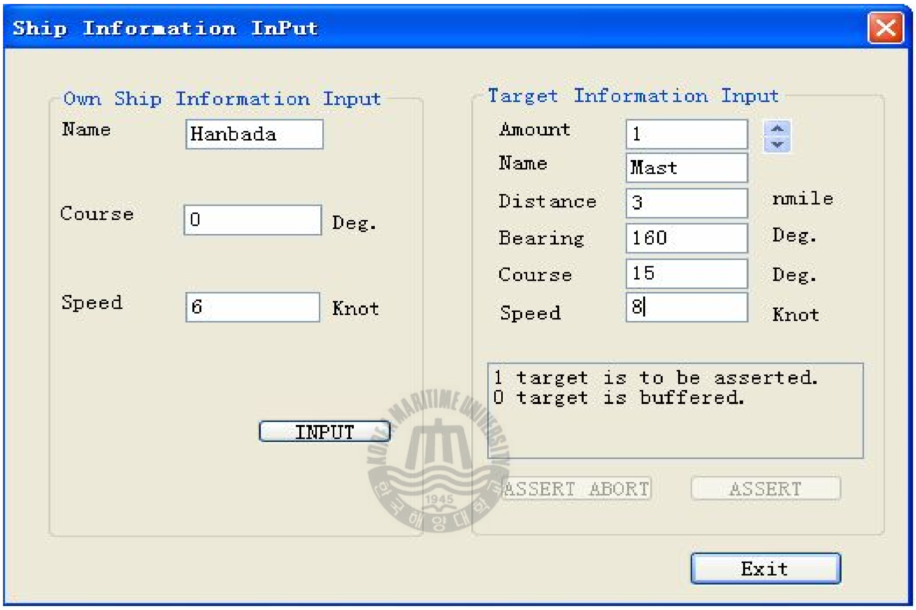


Fig.4-9 Ship Information Input Dialog Box

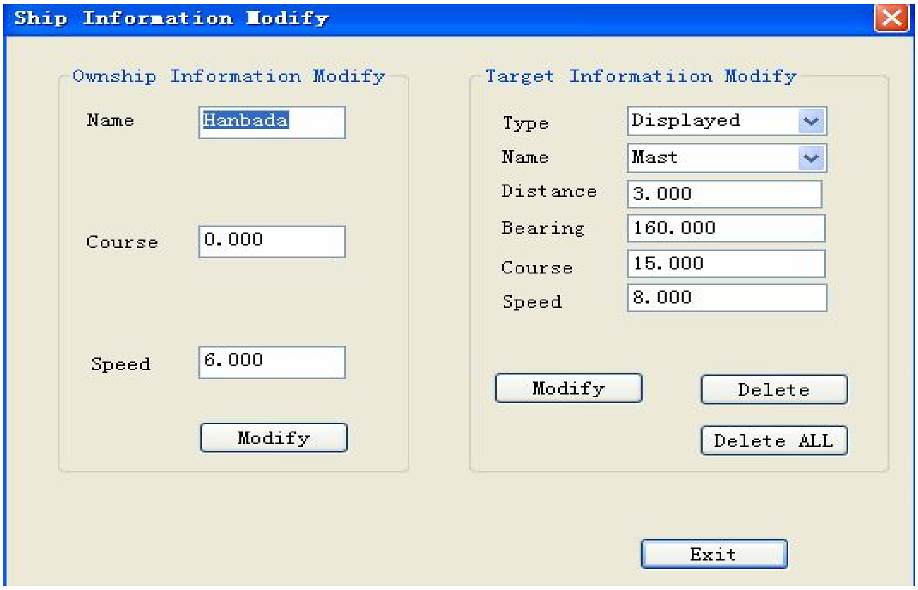


Fig.4-10 Ship Information Modify Dialog Box

By using ship information modify dialog, users can modify navigational information of own ship and targets. Moreover, users can delete one target or delete all of them.

4.9.2.5 Approaches of Receiving Information

In addition to receiving the data inputted by users, ESCAN can receive information by using three approaches. And they are 'Read from file', 'Read from UDP port' and 'Read from COM port'. And users can use the menu(Fig.4-3) to select one of the three approach. 'Read from file' is to read the recorded files which record some specific situations; 'Read from UDP' is to read navigational data provided by some other S/W from UDP port; 'Read from COM' is to read navigational data directly from COMs of Computers. Users can use the different approaches for normal navigation, practice, simulation and so on.

4.10 Using ESCAN to Deal with Single Target-ship Encountering Situations

4.10.1 Head-on Situation

If navigational information of own ship and a target is the data just as shown in Table 4-2, and the situation can be described as shown in Fig.4-11. Recommendation of ESCAN is '*When distance from the target is less then 4 nm,* *own ship should take course towards starboard 30° and return to original course when collision risk is small, and the safe zone to it is [80.8°,279.2°]'*. This recommendation can be simulated by using simulation function of ESCAN as shown in Fig.4-12.

Regulation for dealing with head-on situation in COLREG 1972 is RULE 14 as follows: '*When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.*'

Table 4-2 Data of a Head-on Situation

Head-on Situation	Own Ship	Target-Ship
Distance(nm)	--	4.5
Bearing(°)	--	0
Course(°)	000	180
Speed(knot)	10	10

Table 4-3 Data of an Overtaking Situation

Overtaking Situation	Own Ship	Target-Ship
Distance(nm)	--	2.2
Bearing(°)	--	355
Course(°)	000	0
Speed(knot)	10	2

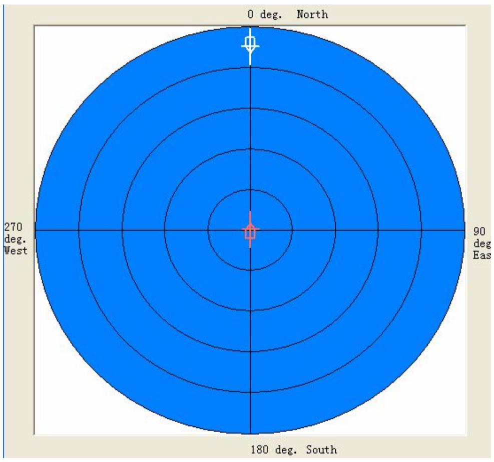


Fig.4-11 An Example of Head-on Situation

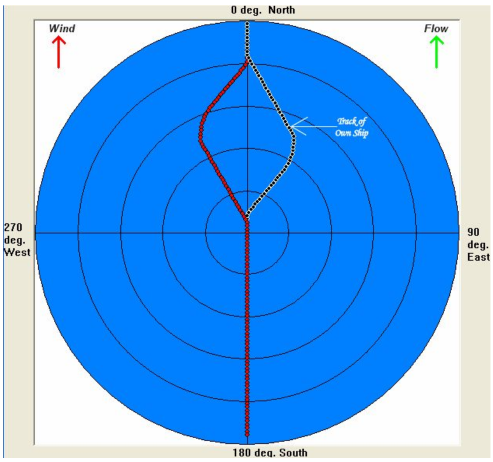


Fig.4-12 Simulation of a Head-on Situation

And as the simulation result (Fig.4-12) shows, the recommendation provided by ESCAN conforms to RULE 14 well, so it is reasonable.

4.10.2 Overtaking Situation

If navigational information of own ship and a target is the data just as shown in Table 4-3, and the situation can be described as shown Fig.4-13. Recommendation of ESCAN is '*When distance from the target is less then 2 nm, own ship should take course towards starboard 20°and return to original course when collision risk is small, and the safe zone to it is [70.3°,279.7°]*'. This recommendation can be simulated by using simulation function of ESCAN as shown in Fig.4-14.

Regulation for dealing with overtaking situation in COLREG 1972 is RULE 13 as follows:

'*Notwithstanding anything contained in the Rules of Part B, Section I and II, any vessel overtaking any other shall keep out of the way of the vessel being overtaken.*'

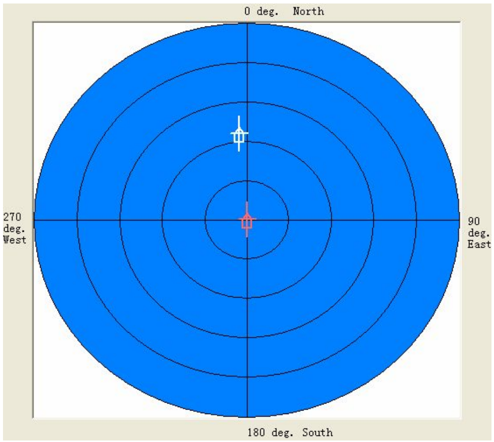


Fig.4-13 An Example of Overtaking Situation

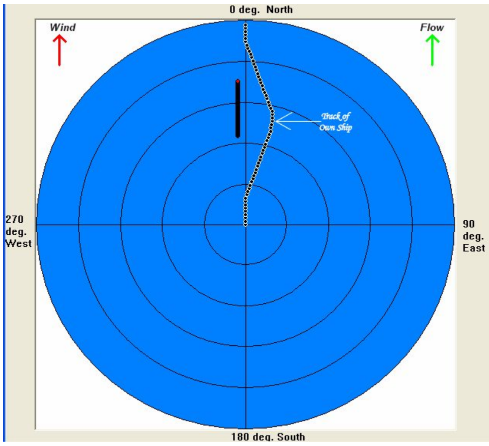


Fig.4-14 Simulation of an Overtaking Situation

And as the simulation result (Fig.4-14) shows, the recommendation provided by ESCAN conforms to RULE 13 well, so it is reasonable.

4.10.3 Crossing Situation

In section 4.9.1, a crossing situation example has been discussed. And the relevant recommendation for dealing with the situation is simulated and displayed in Fig.4-6.

Regulation for dealing with crossing situation in COLREG 1972 is RULE 15 as follows:

‘*When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.*’

And as the simulation result (Fig.4-6) shows, the recommendation provided by ESCAN conforms to RULE 15 well, so it is reasonable.

4.11 Using ESCAN to Deal with Multiple Target-ships Encountering Situations

By using the approach discussed in section 2.4.7, ESCAN can deal with multiple target-ships encountering situations to some extent. A example can be used to demonstrate how ESCAN deal with such situations.

If navigational information of own ship and two targets is the data just as shown in Table 4-4, and the situation can be displayed as shown in Fig.4-15.

Table 4-4 Data of One Two-target Encountering Situation-1

	Own Ship	Target-ship A	Target-ship B
Distance(nm)	--	3.5	4.0
Bearing(º)	--	45	330
Course(º)	000	235	145
Speed(knot)	10	10	12

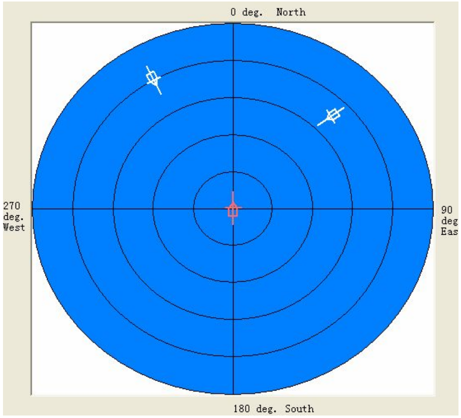


Fig.4-15 An Example of Two-target Encountering Situation-1

ESCAN will deal with this situation as follows:

4.11.1 Determining Encountering Situation with Each Target-ship

Firstly, according the navigational information, ESCAN will determine encountering situation with each target-ship and calculate value of collision risk for each of them. In order to evaluate risk of collision between own ship and targets, mathematical approaches should be used. In ESCAN, Equation (2-2) introduced in Chapter 2 is used to evaluate the value of collision risk.

$$CR = \frac{p.\sec h(a.dcpa)}{ta} + r.\phi(\theta,\alpha) \qquad (2\text{-}2)$$

And the information provided by ESCAN is as shown in Fig.4-16.

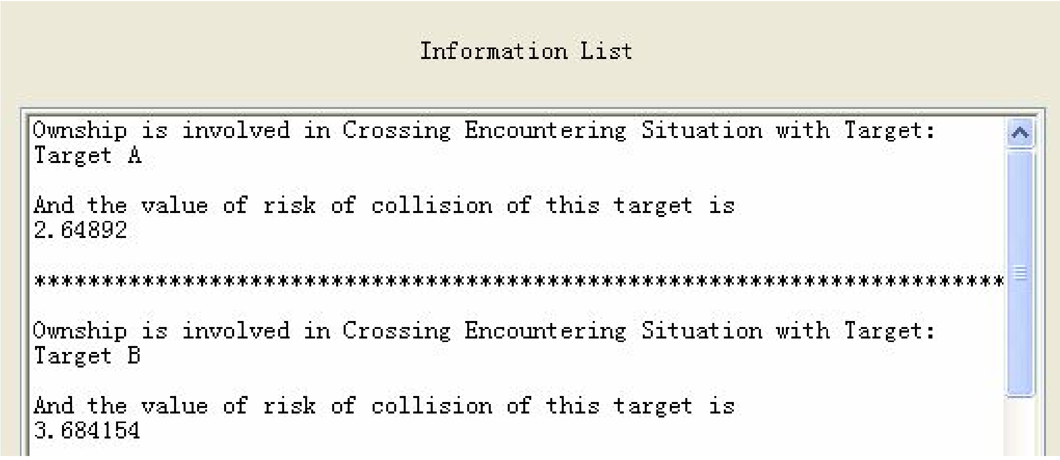


Fig.4-16 Information of Determining Encountering Situations

As shown in Fig.4-16, own ship is involved in crossing encountering situation with *Target A* and *Target B* and the values of collision risk of them are 2.64892 and 3.684154 respectively.

4.11.2 Selecting the Primary Target-ship to Avoid

COLREGS does not provide detailed regulations for dealing with collision avoidance of multi-target encountering situations, so navigators usually use the approach that they select a target-ship which is considered the most dangerous one as the primary target-ship to avoid. The approach can deal with ordinary multi-target encountering situations. ESCAN uses it as the default approach for dealing with multi-target encountering situations.

Recommendation of ESCAN is shown in Fig.4-17.

```
**************************************************************************
The value of collision risk of 'Target A' : 2.6489203
The value of collision risk of 'Target B' : 3.6841540

**************************************************
So the target which has the maximum value of risk of collision is
Target B

And its value of risk of collision is
3.684154

**************************************************************************
```

Fig.4-17 Information of Selecting Primary Target

As shown in Fig.4-17, the values of collision risk of targets are 2.64892 and 3.684154 respectively. So *Target B* is the primary target.

4.11.3 Determining Avoiding Action and Timing to Take

```
**************************************************************************
Now own ship is in Region 6 Crossing State with Target:
Target B

GAGES-013

The collision avoidance action steps and other business
are as follows:

0.)Timing:
    Target's approaching speed is less than 30 knots,
  own ship should take action when distance is less then
  4 nmiles;

1.)Steps:
    1. Starboard change course until target's relative
       bearing is 270 deg.
    2. Rudder angle should be bigger than 10 deg.
    3. Whilst using whistle and flash signal, send signal
       1 short whistles and 1 flashes once

2.)Confirm:
    When action is finished, target's new DCPA near 2 miles,
  meanwile if starboard aspect is decreased, and is changing
  to port aspect,it is thought there is no more danger. But
  at this time if DCPA is decreased to less than 2 miles,
  and target's starboard aspect is increased that means
  target has taken port course changed action. Own ship
  should continues to take starboard course 10 deg. each
```

Fig.4-18 Information of Avoiding Actions

According to 4.11.1 and 4.11.2, avoiding action for avoiding *Target B* can be determined. And because relative approaching speed of the target is less than 30 knots, timing to take actions is when the distance from own ship is less than 4 miles. That is to say, the action should be taken immediately because the condition is already met. And the detailed information provided by ESCAN is as shown in Fig.4-18.

4.11.4 Determining Safe Action Zone

In section 4.9.2.2, safe zone calculation function is discussed. Also, in multiple target-ships encountering situations, safe zones of multiple targets can be acquired by using the function and should be considered by navigators during the process of taking avoiding actions. And the information of safe action zone is also provided by ESCAN and is shown in Fig.4-19.

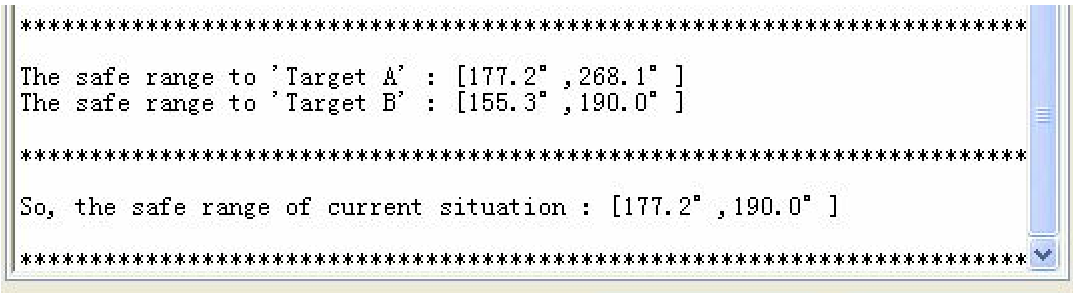


Fig.4-19 Information of Safe Action Zone

As shown in Fig.4-19, safe action zone to *Target A* is [177.2°, 268.1°] and that to *Target B* is [155.3°, 190.0°]. So the safe action zone of current situation is [177.2°, 190.0°]. This zone is very important and should be considered when avoiding action is taken.

4.11.5 Simulating the Determined Avoiding Action

Finally, the action can be simulated by using simulation function of ESCAN, and the result of simulation is shown in Fig.4-20.

As the simulation result (Fig.4-20) shows, the recommendation effectively reduces the collision risk, so it is appropriate.

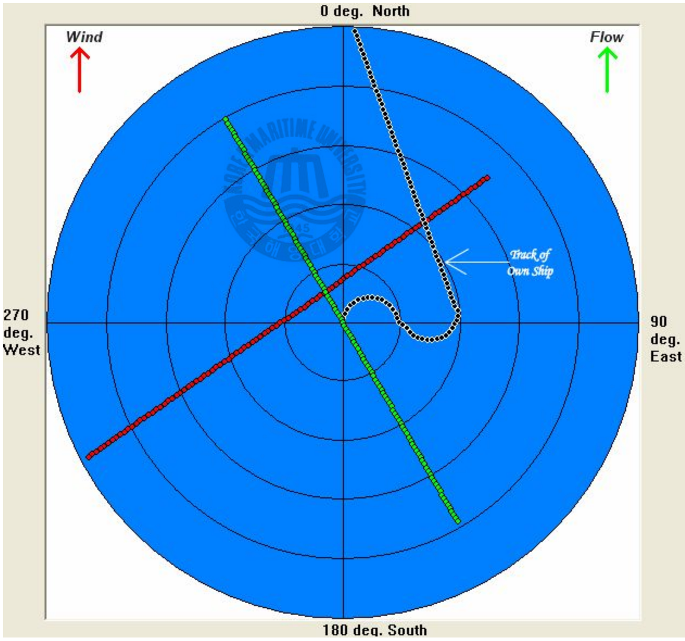


Fig.4-20 Simulation of Two-target Encountering Situation-1

Moreover, in some situations, the one which does not have maximum value of collision risk should be selected as the primary target to avoid. ESCAN provides a function that allows users to select a specific target as the primary target on simulation dialog. Therefore, in such situations, if users think the recommendation of ESCAN is not proper, they can select a different target-ship as the primary target and simulate the situation so as to find an appropriate avoiding plan.

For example, if navigational information of own ship and two targets is the data just as shown in Table 4-5, and the situation can be displayed as shown in Fig.4-21.

Default recommendation of ESCAN is to select the target which is dead ahead as the primary target to avoid. But if own ship only avoids the target dead ahead, she may become involved in new collision risk with the other target which is on her starboard side. So users can change the primary target by using the dialog in Fig.4-22 and simulate the new situation.

Table 4-5 Data of One Two-target Encountering Situation-2

	Own Ship	Target-ship A	Target-ship B
Distance(nm)	--	4	4
Bearing(°)	--	45	0
Course(°)	000	235	180
Speed(knot)	5	5	5

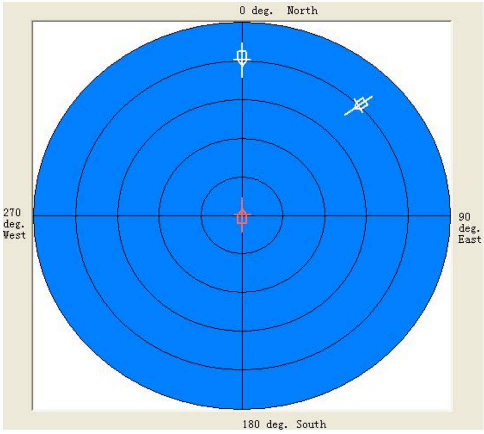


Fig.4-21 An Example of Two-target Encountering Situation-2

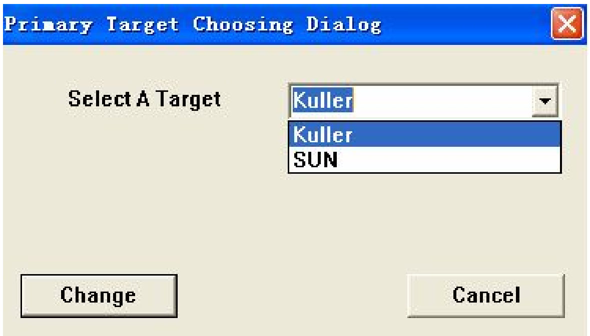


Fig.4-22 Change Primary Target

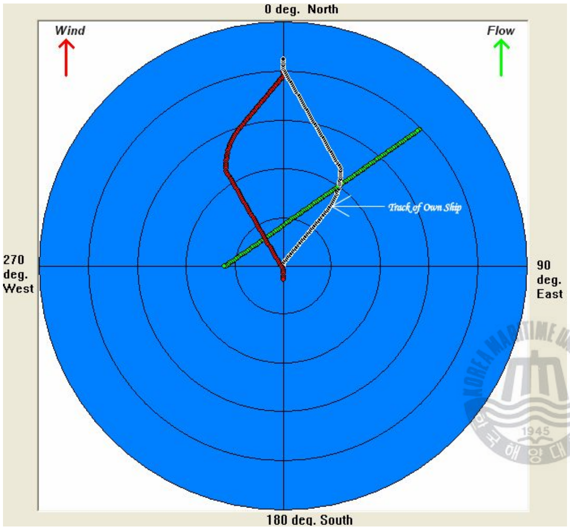


Fig.4-23 Simulation of Default Recommendation

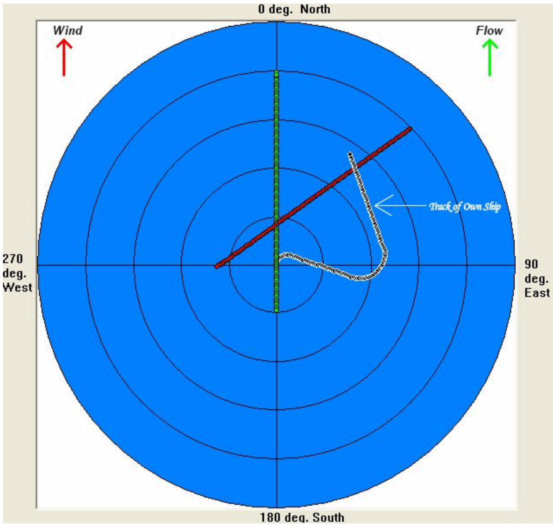


Fig.4-24 Simulation When the Primary Target is Changed

Assuming the two targets keep their course and speed, Fig.4-23 is the simulation result of selecting the target dead ahead as the primary target and Fig.4-24 is the simulation result of selecting the other target as the primary target.

As the simulation results (Fig.4-23, Fig.4-24) show, Fig.4-24 is more reasonable for dealing with this situation.

4.11.6 Multi-target Encountering Case Matching

4.11.6.1 Automatic Scene Matching Function

In order to utilize good experience and good seamanship of some practical cases, ESCAN records them and matches them in real time. If some case matches current situation, ESCAN will activate it and display its relevant avoiding action and other description on a popup dialog.

For example, Case001 contains the information is shown in Table 4-6.

Table 4-6 Information of Case001

Case001	Own Ship	Target-ship A	Target-ship B	Target-ship C	Target-ship D
Distance(nm)	--	4.0	4.2	3.5	2.0
Relative Bearing(º)	--	1	30	100	165
Course(º)	000	182	215	290	2
Speed(knot)	8	10	13	10	7

And this situation can be described as shown in Fig.4-25. Precision of the automatic scene matching function can be adjusted on the Matching Precision Setting Dialog as shown in Fig.4-26. When current situation matches the conditions of Case001, Case001 will be activated, and a dialog as shown in Fig.4-27 will pop up. Conditions of a case contain visibility situation, type of water area, number of involved targets and detailed navigational information of own ship and target ships when the case happened.

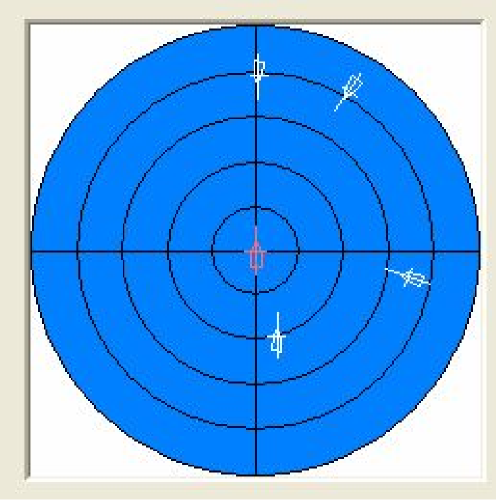


Fig.4-25 Description of Case001

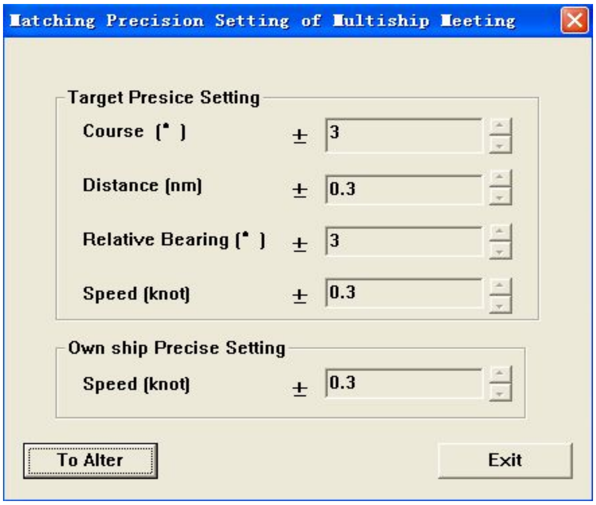


Fig.4-26 Matching Precision Setting Dialog

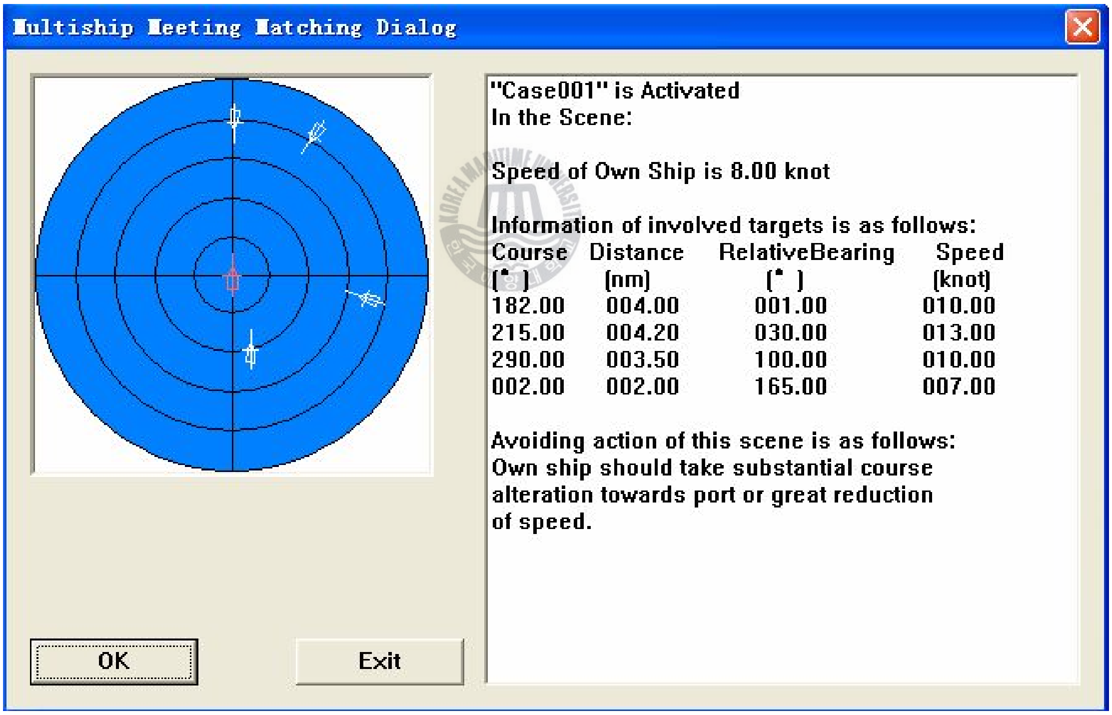


Fig.4-27 Activated Scene Matching Dialog Box for Case001

During navigation, complicated situations like Case001 may happen, recommendations provided by ESCAN may not be quite appropriate to deal with those situations. At that time, if the automatic scene matching function of ESCAN can find a similar case which matches current situation and provide relevant avoiding actions, this will greatly help users to know current situation so as to make a reasonable decision of collision avoidance in time. However, some actions of these cases may not well conform to COLREGS, and they are for reference only.

4.11.6.2 Browsing Multi-target Encountering Cases

ESCAN also provides users with a dialog box for browsing the recorded multi-target encountering cases. One the dialog box as shown in Fig.4-28, uses can easily browse each case and acquire relevant information of it.

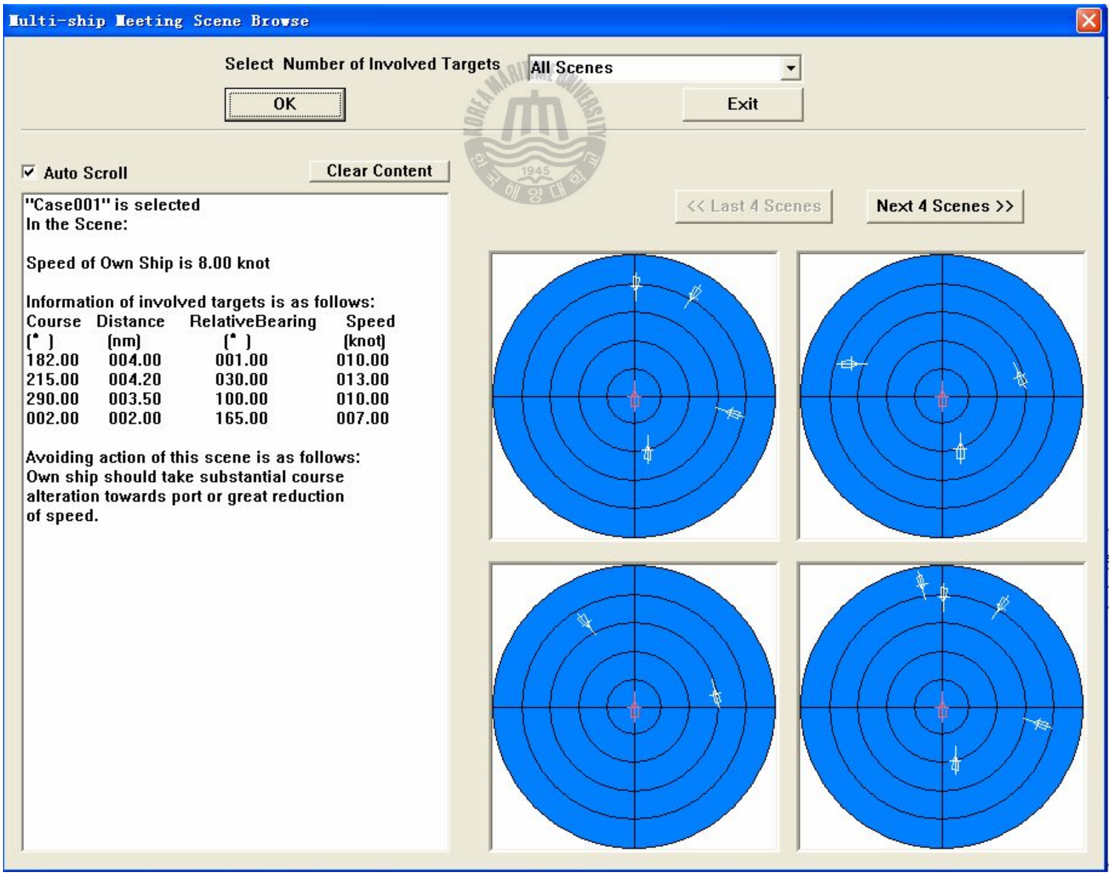


Fig.4-28 Multi-ship Encountering Case Browse Dialog

Sometime, even a case not match current situation, but it may be similar to current situation, users can browse these cases as reference so as to make a more reasonable decision of collision avoidance. As shown in Fig.4-28, cases can be browsed by the amount of involved targets of cases.

Chapter 5 Conclusion

Along with large-sized and high-speed trends in ships, marine accidents are increasing in probability, and once they happen the secondary losses such as marine pollution as well as the primary losses of human and property are swelling rapidly[31]. However, collision avoidance is still a difficult problem to be solved. As a method to reduce these accidents, an expert system for collision avoidance and navigation (ESCAN) is proposed in this paper. With use of AIS technology, the ESCAN can receive more useful navigational information of other ships in the vicinity of own ship so as to provide new seafarers with more sophisticated recommendations or suggestions for dealing with current situation. Some main conclusions of this paper are drawn as followings.

Firstly, COLREGS, the process of collision avoidance and some other related aspects are discussed here. Some results are given as follows:

(1) In order to prevent and avoid collisions at sea, and to secure safe navigation of ships, COLREGS needs to be correctly comprehended and strictly carried out.

(2) Safe speed is a primary factor ensuring if own ship has enough time to determine and take proper and effective avoidance actions. During navigation, it should be appropriately determined so as to adapt to prevailing circumstances and conditions.

(3) Safe passing distance should be maintained during navigation. Normally in

open sea two(2) nautical miles are considered to be sufficient.

(4) Encountering process of two ships can be divided into 4 phases such as phase of effect-free action, phase of involving risk of collision, phase of involving close-quarters situation and phase of involving danger of collision.

(5) Usually, navigators use value of collision risk to know the risk of collision and to select the primary target to avoid. In ESCAN, formula (2-2) is used to appraise the value of collision risk.

(6) If own ship is involved in a multi-target encountering situation, ESCAN will analyze the encountering situations between own ship and other ships, predict possible movement of other ships, determine which target is the primary one to avoid, and determine avoiding action and the time to take. Meanwhile, navigators should also consider the safe passing distance of current situation and the safe zone of collision avoidance provided by ESCAN. By using this approach, appropriate decision-making for dealing with current multi-target encountering situation of can be acquired.

Secondly, detailed design of ESCAN is introduced and some results can be drawn as follows:

(1) The ESCAN is designed and developed by using the theory and technology of expert system and based on information provided by AIS and radar/ARPA system.

(2) It is composed of four components. Facts/Data Base in charge of

preserving data from navigational equipment, Knowledge Base storing production rules of the ESCAN, Inference Engine deciding which rules are satisfied by facts, User-System Interface for communication between users and ESCAN.

(3) In ESCAN, AIS technology is used. AIS can help own ship to receive more detailed navigational information from the ships in the vicinity of her. Therefore, more reasonable decision-making can be determined according to such abundant information.

(4) Navigational knowledge used in ESCAN is based on COLREGS and other navigation expertise.

(5) Module structure is used to build the knowledge base of ESCAN. And it is divided into six modules such as basic navigational rules module, maneuverability judgment module, division of encountering phase module, encountering situation judgment module, auxiliary knowledge of collision avoidance module, and navigation experience and multi-ship encountering scene avoiding action module.

(6) Production rules are used to represent the knowledge of collision avoidance in ESCAN because the structure of them is perfect for representing such knowledge and they are supported by CLIPS well.

(7) A new inference process of collision avoidance as shown in Fig.3-8 is used in ESCAN.

(8) Mixed inference which combines forward inference and backward inference is used in ESCAN.

(9) Because CLIPS adopts Rete Pattern-Matching Algorithm, response speed of ESCAN is greatly increased.

Finally, detailed implementation of ESCAN is introduced and some conclusions are given as follows:

(1) The part of ESCAN in charge of inference is programmed in CLIPS and the remaining part of it is programmed in Visual C++.
(2) The ESCAN has the function of real-time analysis and judgment of various encountering situations between own ship and targets, and is to provide navigators with appropriate plans of collision avoidance and additional advice and recommendation.
(3) Auxiliary functions of ESCAN are convenient for users such as simulation function which can simulate avoiding actions provided by ESCAN.
(4) According to the results of the examples, the suggestions provided by ESCAN conform to the rules of COLREGS and the advice given by navigation experts well.
(5) It is easy to upgrade ESCAN when rules are required to be upgraded in the future. Only rules in Knowledge Base should be rewritten rather than the whole system.
(6) Multi-target encountering case matching function of ESCAN can provide a recorded reference case for dealing with current situation if all the conditions of the case are matched.

Development of ESCAN not only can help navigators to make more reasonable decision-making of collision avoidance so as to ensure safe navigation of ships, but also can positively promote the development of integrated automatic navigation system which integrates all shipborne systems and implements intelligent unmanned navigation. However, some problems such as upgrading rules for dealing with complicated multi-target encountering situations or integrating ESCAN with other shipborne systems still need to be kept researching and studying in the future.

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Annex I Content of COLREGS

The 1972 Regulations contain 5 parts, 38 rules and 4 annexes. Detailed contents are shown as follows:

- Part A - GENERAL
  - Rule 1 Application
  - Rule 2 Responsibility
  - Rule 3 General Definitions
- Part B - STEERING AND SAILING RULES
  - Section I - Conduct of Vessels in any Condition of Visibility (7 Rules)
    - Rule 4 Application
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ANNEX I, II, III, IV (Omission)

List of Published Papers during Doctoral Course

Journals:

1. Jeong, T.G. and Chen, C. (2007), "*A Modification of the Approach to the Evaluation of Collision Risk Using Sech Function*", Journal of Korean Navigation and Port Research, Vol.31, No.2 pp.121~126.
2. Jeong, T.G. and Chen, C. (2008), "*A Study of Development of Expert System for Collision Avoidance and Navigation (I): Basic Design*", Journal of Korean Navigation and Port Research, Vol.32, No.7 pp.529~535.

Proceedings:

1. Jeong, T.G. and Chen, C. (2006), "*A Modification of the Approach to the Evaluation of Collision Risk Using Sech Function*", Proceeding of 12th IAIN World Congress 2006 International Symposium on GPS/GNSS, Vol.1. pp.83~88.
2. Jeong, T.G. and Chen, C. (2007a), "*Development of Collision Avoidance Expert System by Using CLIPS and Visual C++(I)*", Proceeding of Spring Academic Conference of Korean Institute of Navigation and Port Research, Vol.31, No.1,pp.21~26.

3. Jeong, T.G. and Chen, C. (2007b), "*Simulating Avoidance Actions and Evaluating Navigational Rules in An Expert System of Collision Avoidance*", Proceeding of Autumn Academic Conference of Korean Institute of Navigation and Port Research, Vol.31,No.2, pp.79~80. This paper wins Excellent Presentation Award of this conference.
4. Jeong, T.G. and Chen, C. (2008a), "*A Study on Development of Expert System for Collision Avoidance and Navigation (ESCAN)(II)--A Simulation Study--*", Proceeding of 2008 Association Academic Conference "Environmental Change on the Earth and Prospect of Marine Industry ", pp.38~39.
5. Jeong, T.G. and Chen, C. (2008b), "*A Study on Development of Expert System for Collision Avoidance and Navigation (ESCAN) Based on AIS*", Proceedings of Asia Navigation Conference 2008, pp.15~22. This paper wins Best Paper Award of ANC 2008.

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