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Autonomous guidance and navigation based on the COLREGs rules and regulations of collision avoidance.

L. P. Perera
Centre for Marine Technology and Engineering (CENTEC), Technical University of Lisbon, Instituto Superior Tecnico, Lisbon, Portugal

J. P. Carvalho
INESC-ID, Technical University of Lisbon, Instituto Superior Tecnico, Lisbon, Portugal

C. Guedes Soares
Centre for Marine Technology and Engineering (CENTEC), Technical University of Lisbon, Instituto Superior Tecnico, Lisbon, Portugal

ABSTRACT: Autonomous Guidance and Navigation (AGN) is meant to be an important part of the future ocean navigation due to the associated navigational cost reduction and maritime safety. Furthermore intelligent decision making capabilities should be an integrated part of the future AGN system in order to improve autonomous ocean navigational facilities. This paper is focused on an overview of the AGN systems with respect to the collision avoidance in ocean navigation. In addition, a case study of a fuzzy logic based decision making process accordance with the International Maritime Organization (IMO) Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) has been illustrated.

1 INTRODUCTION

1.1 *Autonomous guidance and navigation*

"Automatic steering is a most valuable invention if properly used. It can lead to disaster when it is left to look after itself while vigilance is relaxed. It is on men that safety at sea depends and they cannot make a greater mistake than to suppose ..."

The statement was made by the Justice Cairns with respect to a collision that had occurred due to the fault in the automatic pilot system when the British cargo ship "Trentbank" was overtaking the Portuguese tanker "Fogo"' in the Mediterranean in September 1964 (Cockcroft and Lameijer (2001)). The verdict not just shows the importance of the AGN systems in ocean navigations but also of the human vigilance of its capabilities and requirements for further developments.

The automatic pilot systems are primary level developments units of the Autonomous Guidance and Navigation (AGN) Systems and their applications have been in the dreams of ship designers in several decades. The development of computer technology, satellite communication systems, and electronic devices, including high-tech sensors and actuators, have turned these dreams into a possible reality when designing the next generation ocean AGN systems.

The initial step of the AGN system, which made the foundation for applied control engineering, was formulated around 1860 to 1930 with the invention of the first automatic ship steering mechanism by Sperry (1922). Sperry's work was based on replication of the actions of an experienced helmsman that was formulated as a single input single output system (SISO).

Similarly, the research work done by Minorski (1922) is also regarded as the key contribution to the development of AGN Systems. His initial work was based on the theoretical analysis of automated ship steering system with respect to a second order ship dynamic model. The experiments were carried out by Minorski on New Mexico in cooperation with the US Navy in 1923 and reported in 1930 (Bennett, 1984).

Hence both works done by Sperry and by Minorski are considered as the replication of non-linear behavior of an experienced helmsman (Roberts et al. (2003)) in ocean navigation. From Sperry's time to present, much research has been done and considerable amount of literature has been published on AGN systems with respect to the areas of marine vessel dynamics, navigation path generations, and controller applications, environmental disturbance rejections and collision avoidance conditions.

The functionalities of the Multipurpose Guidance, Navigation and Control (GNC) systems are summarized by Fossen (1999) on a paper that focuses not only on course-keeping and course-changing maneuvers (Conventional auto pilot system) but also integration of digital data (Digital charts and weather data), dynamic position and automated docking systems.

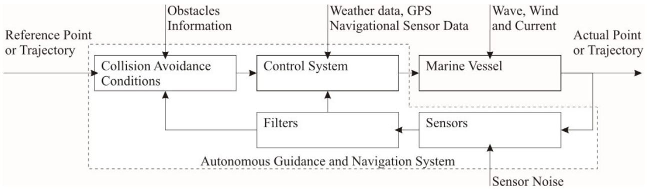

Figure 1: Autonomous Guidance and Navigation System.

Recent developments of design, analysis and control of AGN systems are also summarized by Ohtsu (1999), and several ocean applications of AGN systems have been further studied theoretically as well as experimentally by (Moreira et al., (2007); Healey and Lienard, (1993); Do and Pan, (2006)). This area is bound to become increasingly important in the future of ocean navigation due to the associated cost reduction and maritime safety.

The block diagram of main functionalities of a AGN system integrated with collision avoidance facilities is presented in Fig. 1. The AGN system contains four units of Collisions Avoidance Conditions (CAC), Control System(CS), Filters and Sensors. The sensor unit consists of sensors that could measure course and speed characteristics of the vessel navigation. The filter unit is formulated for filter-out noisy signals. The output of the Filter unit will be feedback into the CAC unit as well as the CS unit. The sensor signals will be used by the CS unit to control overall vessel navigation of the vessel and used by the CAC unit to make decisions on collisions avoidance process.

1.2 *Collision avoidance*

Having an intelligent decision making process is an important part of the future AGN systems in ocean navigation. However, conventional ocean navigational systems consist of human guidance, and as a result, 75-96 % of marine accidents and causalities are caused by some types of human errors (Rothblum et al. (2002); Antão and Guedes Soares 2008). Since most of the wrong judgments and wrong operations of humans at the ocean ended in human casualties and environmental disasters, limiting human subjective factors in ocean navigation and replacing them by an intelligent Decision Making (DM) system for navigation and collision avoidance could reduce maritime accidents and its respective causalities. However development of collision avoidance capabilities into the next generation AGN systems in ocean navigation is still in the hands of future researchers and this part of the intelligent AGN systems has been characterized as e-Navigation (eNAV (2008)).

The terminology used in recent literature regarding the collision avoidance conditions designates the vessel with the AGN system as the ”Own vessel”, and the vessel that needs to be avoided as the ”Target vessel”. With respect to the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) rules and regulations, the vessel coming from the starboard side has higher priority for the navigation and is called the ”Stand on” vessel and the vessel coming from the port side has lower priority and is called the ”Give way” vessel. These definitions have been considered during the formulation of collision situations in this work.

The decision making process and strategies in interaction situations in ocean navigation, including collision avoidance situations, are presented by Chauvin and Lardjane (2008). The analysis of quantitative data describing the manoeuvres undertaken by ferries and cargo-ships and behaviour of the ”Give way” and the ”Stand on” vessels with respect to verbal reports recorded on board a car-ferry in the Dover Strait are also presented in the same work.

The detection of the Target vessel position and velocity are two important factors assessing the collision risk in ocean navigation as illustrated in recent literature. Sato and Ishii (1998) proposed combining radar and infrared imaging to detect the Target vessel conditions as part of a collision avoidance system. The collision risk has been presented with respect to the course of the Target vessel and image processing based course measurement method proposed in the same work.

The vessel domain could be defined as the area bounded for dynamics of the marine vessel and the size and the shape of the vessel domain are other important factors assessing the collision risk in ocean navigation. Lisowski et al. (2000) used neural-classifiers to support the navigator in the process of determining the vessel’s domain, defining that the area around the vessel should be free from stationary or moving obstacles. On a similar approach, Pietrzykowski and Uriasz (2009) proposed the notion of vessel domain in a collision situation as depending on parameters like vessel size, course and heading angle of the encountered vessels. Fuzzy logic based domain determination system has been further considered in the same work.

Kwik (1989) presented the calculations of two-ship collision encounter based on the kinematics and dynamics of the marine vessels. The analysis of collision avoidance situation is illustrated regarding the vessel velocity, turning rate and direction, and desired passing distance in the same work. Yavin et al. (1995) considered the collision avoidance conditions of a ship moving from one point to another in a narrow zig-zag channel and a computational open loop command strategy for the rudder control system associated with the numerical differential equation solver is proposed. However, the dynamic solutions based on differential equations could face implementation difficulties in real-time environment.

The design of a safe ship trajectory is an important part of the collision avoidance process and has usually been simulated by mathematical models based

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on manoeuvring theory (Sutulo et al. 2002). An alternative approach based on neural networks has also been proposed by Moreira and Guedes Soares (2003). Optimization of a safe ship trajectory in collision situations by an evolutionary algorithm is presented by Smierzchalski and Michalewicz (2000), where comparison of computational time for trajectory generation with respect to other manoeuvring algorithms, and static and dynamic constrains for the optimization process of the safe trajectories are also illustrated. However, the optimization algorithms always find the solution for the safe trajectory based on assumptions; hence the optimum solutions may not be realistic and may not have intelligent features. As an example, it is observed that some of the optimization algorithms always find the safest path behind the Target vessel and that may lead to a conflict situation with the COLREGs rules and regulations.

1.3 *The COLREGs*

It is a fact that the COLREGs rules and regulations regarding collision situations in ocean navigation have been ignored in most of the optimization algorithms. The negligence of the IMO rules may lead to conflicts during ocean navigation. As for the reported data of the maritime accidents, 56% of the major maritime collisions include violation of the COLREGS rule and regulations (Statheros et al. (2008)). Therefore the methods proposed by the literature ignoring the COLREGs rules and regulations should not be implemented in ocean navigation. On the other hand, there are some practical issues on implementation of the COLREGs rules and regulations during ocean navigation. Consider the crossing situations where the Own vessel is in "Give way" situations in Figures 4, 5, 6, and 7 and in "Stand on" situations in Figures 9, 10, 11 and 12, there are velocity constrains in implementing COLREGs rules and regulations of the "Give way" and the "Stand on" vessels collision situations when the Target vessel has very low or very high speed compared to the Own vessel.

In the collision avoidance approach of repulsive force based optimization algorithms proposed by Xue et al. (2009), the Own vessel is kept away from the obstacles by a repulsive force field. However this approach may lead to conflict situations when the moving obstacles present a very low speed or very high speed when compared to the Own vessel speed. In addition, complex orientations of obstacles may lead to unavoidable collision situations. On the other hand, repulsive force based optimization algorithms are enforced to find the global safe trajectory for Own vessel navigation, and this might not be a good solution for the localized trajectory search. In addition the concepts of the "Give way" and the "Stand on" vessels that are derived on COLREGs rules and regulations during the repulsive force based optimization process are not taken into consideration and therefore may not be honoured.

The intelligent control strategies implemented on collision avoidance systems could be categorized as Automata, Hybrid systems, Petri nets, Neural networks, Evolutionary algorithms and Fuzzy logic. These techniques are popular among the machine learning researchers due to their intelligent learning capabilities. The soft-computing based Artificial Intelligence (AI) techniques, evolutionary algorithms, fuzzy logic, expert systems and neural networks and combination of them (hybrid expert system), for collision avoidance in ocean navigation are summarized by Statheros et al. (2008).

Ito et al. (1999) used genetic algorithms to search for safe trajectories on collision situations in ocean navigation. The approach is implemented in the training vessel of "Shioji-maru" integrating Automatic Radar Plotting Aids (ARPA) and Differential Global Position System (DGPS). ARPA system data, which could be formulated as a stochastic predictor, is designed such that the probability density map of the existence of obstacles is derived from the Markov process model before collision situations as presented by Zeng et al. (2001) in the same experimental setup. Further, Hong et al. (1999) have presented the collision free trajectory navigation based on a recursive algorithm that is formulated by analytical geometry and convex set theory. Similarly, Cheng et al. (2006) have presented trajectory optimization for ship collision avoidance based on genetic algorithms.

Liu and Liu (2006) used Case Based Reasoning (CBR) to illustrate the learning of collision avoidance in ocean navigation by previous recorded data of collision situations. In addition, a collision risk evaluation system based on a data fusion method is considered and fuzzy membership functions for evaluating the degree of risk are also proposed. Further intelligent anti-collision algorithm for different collision conditions has been designed and tested on the computer based simulation platform by Yang et al. (2007) Zhuo and Hearn (2008) presented a study of collision avoidance situation using a self learning neuro-fuzzy network based on an off-line training scheme and the study is based on two vessel collision situation. Sugeno type Fuzzy Inference System (FIS) was proposed for the decision making process of the collision avoidance.

1.4 *Fuzzy-logic based systems*

Fuzzy-logic based systems, which are formulated for human type thinking, facilitate a human friendly environment during the decision making process. Hence several decision making systems in research as well as commercial applications have been presented before (Hardy (1995)). The conjunction of human behavior and decision making process was formulated by various fuzzy functions in Rommelfanger, (1998) and Ozen et al., (2004). A fuzzy logic approach for the collision avoidance conditions with integration of the virtual force field has been proposed by Lee et al. (2004). However the simulations results are limited to the two vessel collision avoidance situations. The behaviour based controls formulated with interval programming for collision avoidance of ocean navigation are proposed by Benjamin et al. (2006). Further, the collision avoidance behaviour is illustrated accordance with the Coast Guard Collision Regulations (COLREGS-USA).

Benjamin and Curcio (2004) present the decision making process of ocean navigation based on the interval programming model for multi-objective decision making algorithms. The computational algorithm based on If-Then logic is defined and tested under simulator conditions by Smeaton and Coenen (1990) regarding different collision situations. Further, this study has been focused on the rule-based manoeuvring advice system for collision avoidance of ocean navigation.

Even though many techniques have been proposed for avoidance of collision situations, those techniques usually ignore the law of the sea as formulated by the International Maritime Organization (IMO) in 1972. These rules and regulations are expressed on the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)(IMO (1972)). The present convention was designed to update and replace the Collision Regulations of 1960 which were adopted at the same time as the International Convention for Safety of Life at Sea (SOLAS) Convention (Cockcroft and Lameijer (2001)).

The detailed descriptions of collision avoidance rules of the COLREGs, how the regulations should be interpreted and how to avoid collision, have been presented by Cockcroft and Lameijer (2001). Further, the complexity of autonomous navigation not only in the sea but also in the ground has been discussed by Benjamin and Curcio (2004). The legal framework, rules and regulations, is discussed and the importance of collision avoidance within a set of given rules and regulations is highlighted in the same work.

2 COLREGS RULES AND REGULATIONS

The COLREGs (IMO (1972)) includes 38 rules that have been divided into Part A (General), Part B (Steering and Sailing), Part C (Lights and Shapes), Part D (Sound and Light signals), and Part E (Exemptions). There are also four Annexes containing technical requirements concerning lights and shapes and their positioning, sound signalling appliances, additional signals for fishing vessels when operating in close proximity, and international distress signals.

Three distinct situations involving risk of collision in ocean navigation have been recognized in recent literature (Smeaton and Coenen (1990)), Overtaking (see Figures 3 and 8); Head-on (see Figures 2) and Crossing (see Figures 4 to 7 and 9 to 12) and the rules and regulations with respect to these collision conditions have been highlighted by the COLREGs.

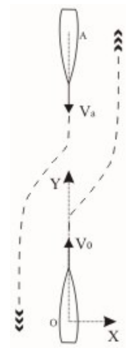

Figure 2: Head-on

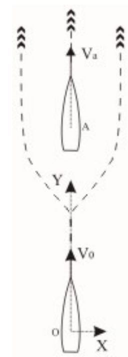

Figure 3: Overtake

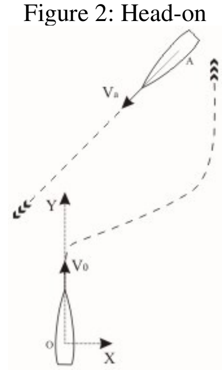

Figure 4: Crossing

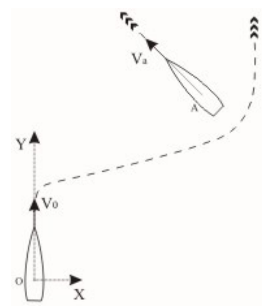

Figure 5: Crossing

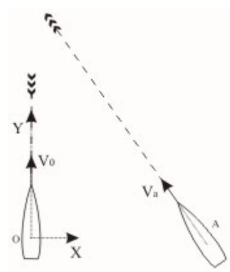

Figure 6: Parallel-crossing

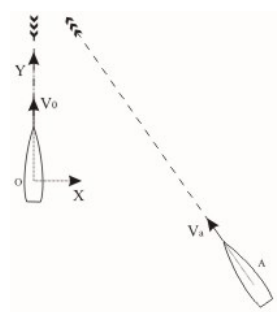

Figure 7: Crossing

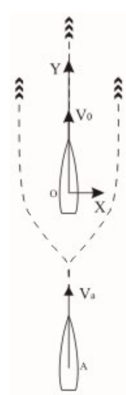

Figure 8: Overtake

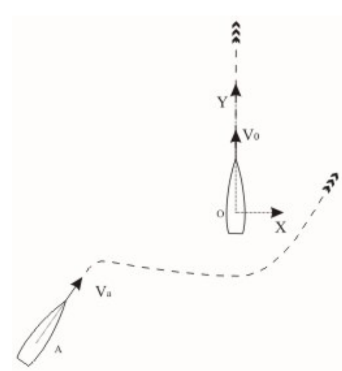

Figure 9: Crossing

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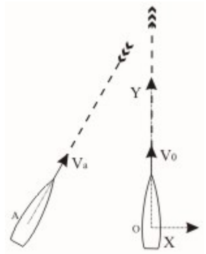

Figure 10: Parallel-crossing

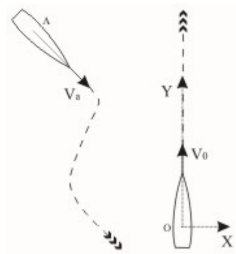

Figure 11: Crossing

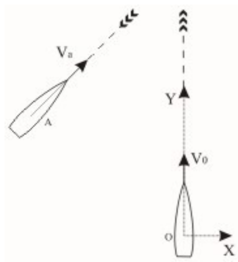

Figure 12: Crossing

The maritime collision could be defined as "a brief dynamic event consisting of the close proximity of two or more stationary or moving ocean obstacles or vessels". Hence, maintenance of safe distance among vessels and other obstacles are important factors of the maritime safety as illustrated by the COLREGs.

The safe distance maintenance by both vessel in a overtake situation (see Figures 3 and 8) has been illustrated by the COLREGs rule 13(a)(IMO (1972)).

"..., any vessel overtaking any other shall keep out of the way of the vessel being overtaken".

Hence both vessels have the responsibility to maintain safe distances during the Overtake encounter. Further, the course change of the head-on situation (see Figure 2) has been specified by the COLREGs rule 13(a)(IMO (1972)).

"When two power-driven vessels 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."

As required by the COLREGs, the vessels should take early action to avoid situations of crossing ahead with the risk of collision in starboard to starboard and must be passing by port to port. The crossing situations further formulated by the COLREGs and according to rule 15

"When a two power-driven vessel are crossing so as to involve risk of collision, the vessel which has the other her own starboard side shall keep out of the wan and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel"

As specified by the COLREGs, the vessel coming from the starboard side has higher priority for the navigation and the vessel coming from the port side has lower priority as mentioned before. This concept is previously defined as the "Give way and the Stand on vessels". However, considering the collision conditions, where the "Give way" vessel did not take any appropriate actions to avoid collisions, as illustrated by the COLREGs rule 17(b) (IMO (1972)), the "Stand on" vessel has been forced to take appropriate actions to avoid collision situation,

"When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the "Give way" vessel alone, she shall take such action as will best aid to avoid collision"

However, the decision making process of the Own vessel in this critical collision situation should be carefully formulated, because the collision avoidance in this situation alternatively depends on the "Stand on" vessel manoeuvrability characteristics. Further, this situation might lead to a "Crash stopping" maneuver of the "Stand on" vessel due the lack of distance for speed reductions. As recommended by the COLREGs rule 6(IMO (1972)) with respect to the reduction of vessel speed for the safe distance,

"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 within a distance appropriate to the prevailing circumstances and conditions. In determining a safe speed the following factors shall be among those taken into account ..."

Hence special factors should be considered for integration of course and speed controls due to the fact that the Own vessel may not response to the required changes of course or speed. Further information with respect to the "Stopping distance" and "Turning circles" should be considered for formations of the decision making process. Vessel course changes and/or speed changes in ocean navigation must be formulated in order to avoid collision situations. The specific controllability of either course or speed change has been highlighted in the COLREGs rule 8(b) (IMO (1972)):

"Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided"

Hence integrated controls of course as well as speed changes should be implemented during ocean navigation to avoid collision situations. Similarly special measures should be considered for integration of course and speed controls due to the fact that the Own vessel may not response to the required changes of course or speed.

3 COLLISION AVOIDANCE METHODOLOGY

3.1 *Identification of Obstacles*

The stationary and moving obstacles in ocean navigation can be identified by several instruments and systems like Eye / camera, radar / Automatic Radar Plotting Aid (ARPA), and Automatic Identification System (AIS). ARPA provides accurate information of range and bearing of nearby obstacles and AIS is capable of giving all the information on vessel structural data, position, course, and speed. The AIS simulator and marine traffic simulator have been implemented on several experimental platforms for design of safe ship trajectories (Hasegawa (2009)).

3.2 *Collection of Navigational Information*

The navigational information of other vessels can be categorized into static, dynamic and voyage related information (Imazu (2006)). Static information is composed of Maritime Mobile Service Identity (MMSI), Call Sign and Name, IMO number, length and beam, type of ship and location and position of communication antenna. Dynamic information can be divided into vessel position, position time stamp, course over ground, speed over ground, heading, navigational status and rate of turn. Finally, voyage related information can be expanded into vessel draft, cargo type, destination and route plan. Collection of navigational information is an important part of the decision making process of the collision avoidance in ocean navigation and can be achieved by collaboration with the Automatic Identification System (AIS).

3.3 *Analysis of Navigational Information*

The collected obstacles and other vessels information should be considered for further analysis of navigational information. However continuous careful observation, collection and analysis of navigational information should be done in small regular intervals to obtain early warning for collision situations. Further in ocean navigation, complex collision situation with the combination of above situation could be occurred and identification of each situation with respect to the each collision conditions will helpfully for the overall decisions on ocean navigation.

3.4 *Assessments of the Collision Risk*

The analysis of navigational information will help to assess the collision risk. The assessment of collision risk should be continuous and done in real-time by the navigational system in order to guarantee the Own vessel safety. As illustrated in the literature, the mathematical analysis of collision risk detection can be divided into two categories (Imazu (2006)): Closest Point Approach Method (CPA - 2D method) and Predicted Area of Danger Method (PAD - 3D method). CPA method consists of calculation of the shortest distance from the Own vessel to the Target vessel and the assessment of the collision risk, which could be predicted with respect to the Own vessel domain. However, this method is not sufficient to evaluate the collision risk since it doesn't take into consideration the target vessel size, course and speed. The extensive study of CPA method with respect to a two vessel collision situation has been presented by Kwik (1989).

The PAD method consists of modelling the Own vessel possible trajectories as an inverted cone and the Target vessel trajectory as an inverted cylinder, being the region of both object intersection categorized into the Predicted Area of Danger. The Target vessel size, course and speed could be integrated into the geometry of the objects of navigational trajectories.

3.5 *Decisions on Navigation*

The decisions of collision avoidance in ocean navigation are based on the speed and course of each vessel, distance between two vessels, distance of the Closest Point of Approach (RDCPA), time to DCPA, neighbouring vessels and other environmental conditions. The decision space of collision avoidance can be categorized into three stages for each vessel in open ocean environment:

- When both vessels are at non collision risk range, both vessels have the options to take appropriate actions to avoid a collision situation;
- When both vessels are at collision risk range, the "Give way" vessel should take appropriate actions to achieve safe passing distance in accordance with the COLREGs rules and regulations and the "Stand on" vessel should keep the course and speed;
- When both vessels are at critical collision risk range, and the "Give way" vessel does not take appropriate actions to achieve safe passing distance in accordance with the COLREGs rules, then "Stand on" vessel should take appropriate actions to avoid the collision situation.

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3.6 *Implementation of Decisions on Navigation*

As the final step, the decisions on vessel navigation should be formulated with respect to the collision risk assessments. The actions that are taken by the Own vessel are proportional to the Target vessel behaviour as well as the COLREGs rules and regulations. The expected Own and Target vessel actions of collision avoidance could be formulated into two categories: Course change and speed change. However the initiation for actions should be formulated with respect to the Target vessel range and the rate of change of range. Further if the actions taken by the Target vessel are not clear or there is doubt about actions, sound signals should be used as recommended by the COLREGs.

In a collision situation, when the Target vessel is ahead or fine on the bow of the Own vessel and the Target vessel overtaking the Own vessel from astern or fine on the quarter without the safe distance, alteration of course is more effective than speed alteration. However in a collision situation, when the Target vessel is approaching from abeam or near the abeam of the Own vessel, alteration of speed is more effective than course alteration but course alteration could be achieved the same.(Cockcroft and Lameijer (2001)). On conventional navigational systems, power driven vessels usually prefer course changes over speed changes due to the difficulties and delays in controllability of engines from the bridge unless the engines are on stand-by mode. However these problems could be overcome with the AGN systems with the integration of speed and course control systems.

4 CASE STUDY: FUZZY LOGIC BASED DECISION MAKING PROCESS

This section focuses on a fuzzy logic based Decision Making (DM) system to be implemented on vessel navigation to improve safety of the vessel by avoiding the collision situations and is an illustration of the study of Perera et al. (2009). The experienced helmsman actions in ocean navigation can be simulated by a fuzzy logic based Decision Making (DM) process, being this one of the main advantages in this proposal.

4.1 *Formation of collision conditions*

Figure 13 presents two vessels in a collision situation in ocean navigation that is similar to a Radar plot in the Own vessel. The Own vessel is initially located at the point O (x_o, y_o), and the Target vessel is located at the point A (x_a, y_a). The Own and Target vessels velocities and course, are represented by V_o, V_a and ψ_o, ψ_a. The relative speed ($V_{a,o}$) and course ($\psi_{a,o}$) of the Target vessel with respect to the Own vessel can be estimated using the range and bearing values in a given time interval. The relative trajectory of the target vessel has been estimated with the derivation of relative speed, $V_{a,o}$ and relative course, $\psi_{a,o}$. All angles have been measured regarding the positive Y-axis. Further, it is assumed that both vessels are power driven vessels regarding the IMO categorization.

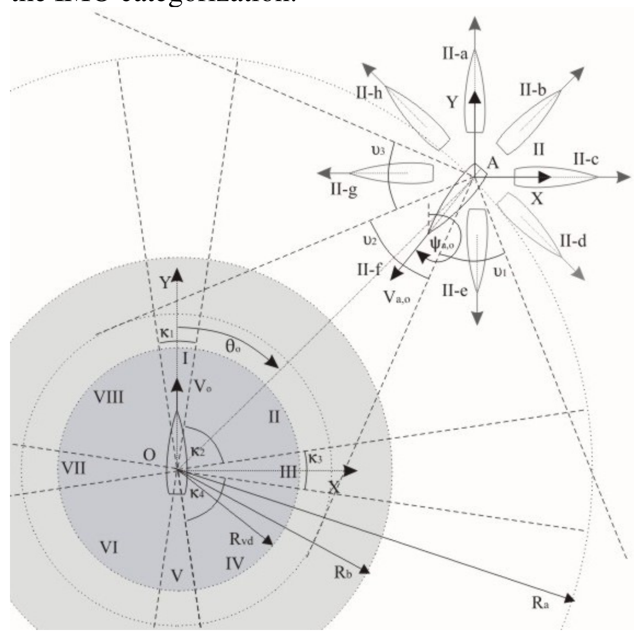

Figure 13: Relative Collision Situation in Ocean Navigation

Further, in Figure 13, the Own vessel ocean domain is divided into three circular sections with radius R_{vd}, R_b and R_a. The radius R_a represents the approximate distance to the Target vessel identification and this distance could be defined as the distance where the Own vessel is in a "Give way" situation and should take appropriate actions to avoid collision. The distance R_b represents the approximate distance where the Own vessel is in "Stand on" situation, but should take actions to avoid collisions due to absence of the appropriate actions from the Target vessel. Further the distance R_{vd} represents the vessel domain. The approximate distances considered for this study are $R_{vd} \approx$ 1NM, $R_b \approx$ 6NM and $R_a \approx$ 10NM.

The Own vessel collision regions are divided into eight regions from I, to VIII. It is assumed that the Target vessel should be located within these eight regions and the collision avoidance decisions are formulated in accordance to each region. As represented in target vessel position II in Figure 13, the Target vessel positions have been divided into eight divisions of vessel orientations regarding the relative course (from II–a to II–h).

4.2 *Fuzzification and Defuzzification*

The overall design process of the fuzzy logic based DM system could be categorized into the following six steps.

– Identification of the input Fuzzy Membership Functions (FMFs).
– Identification of the output FMFs.
– Creation of FMF for each inputs and outputs.
– Construction of If-Then fuzzy rules to operate overall system.
– Strength assignment of the fuzzy rules to execute the actions.
– Combination of the rules and defuzzification of the output.

4.2.1 *Fuzzy Sets and Membership Functions*

Fuzzy sets are defined by Fuzzy Membership Functions (FMF), which can be described as mappings from one given universe of discourse to a unit interval. However it is conceptually and formally different from the fundamental concept of the probability (Pedrycz and Gomide (2007)). A fuzzy variable is usually defined by special FMF called Linguistic Terms that are used in fuzzy rule based inference. The Linguistic terms for the inputs (Collision Distance, Collision Region, Relative Collision Angle and Relative Speed Ratio) and outputs (Speed and Course change of the Own vessel) were defined for this analysis.

Mamdani type "IF <Antecedent i> is <Linguistic Term n> and/or <Antecedent j> is <Linguistic Term m> and/or .... THEN <Consequent> is <Linguistic Term p>" rule based fuzzy system and inference via Min-Max norm was used during this study. On Mamdani fuzzy inference systems, the fuzzy sets resulting from the consequent part of each designed fuzzy rule are combined through an aggregation operator (Ibrahim 2003) according to the activation level of the antecedents. The Min-Max norm is the aggregation operation considered in this study. In this norm the Min (minimum) operator is considered for intersection and Max (maximum) operator is considered for the union of two fuzzy sets.

Finally the defuzzification was made using the center of gravity method. In this method, one calculates the centroid of the resulting FMF and uses its abscissa as the final result of the inference.

4.2.2 *Fuzzy Inference System (FIS)*

The block diagram for Fuzzy Inference System (FIS) with integration of navigational instruments is presented in Figure 14. The initial step of the fuzzy inference system consists of data collection of the target vessel position, speed and course. As the next step, the relative trajectory, relative speed and relative course of the Target vessel are estimated. Then, the data is fuzzified with respect to the input FMF of Collision Distance, Collision Region, Relative Speed Ratio and Relative Collision Angle.

The If-Then fuzzy rules are developed in accordance with the COLREGs rules and regulations and using navigational knowledge. The outputs of the rule based system are the Collision Risk Warning and the Fuzzy Decisions. Finally the fuzzy decisions are defuzzified by output FMF of Course Change and Speed Change to obtain the control actions that will be executed in the Own vessel navigation. The

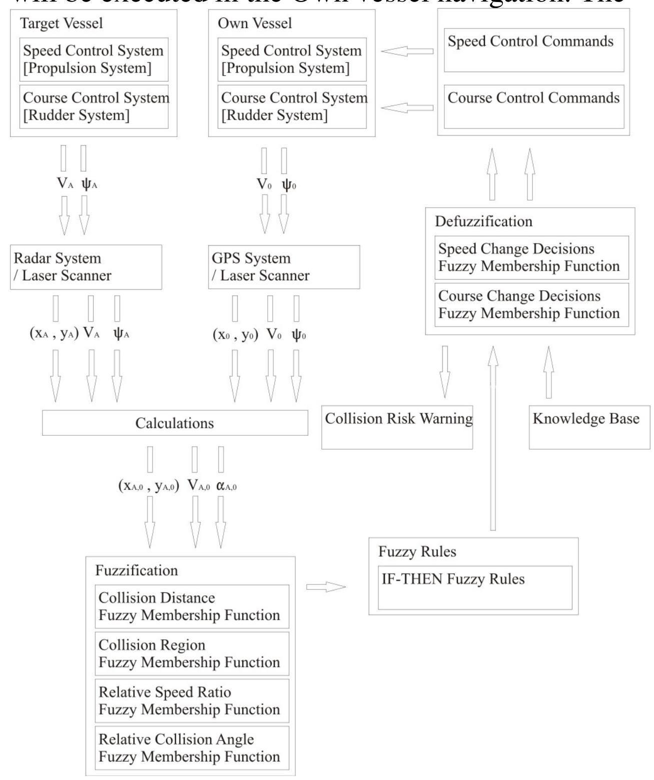

Figure 14: Block diagram for Fuzzy Inference System.

control actions are further expanded as Course control commands and Speed control commands that can be implemented on Rudder and Propulsion control systems as presented in the Figure.

4.2.3 *Computational Implementation*

The fuzzy logic based DM system has been implemented on the software platform of MATLAB. MATLAB has support for the fuzzy logic schemes Mamdani and Sugeno Types (Sivanandam et al. (2007)). However this work has been implemented on the Mamdani based Fuzzy Inference System (FIS). The Mamdani type fuzzy logic scheme consists of utilizing membership functions for both inputs and outputs. As previously mentioned, If-Then rules are formed by applying fuzzy operations into the Mamdani type membership functions for given inputs and outputs.

The MATLAB simulations for two vessels collision situations with respect to the different speeds and course conditions in the Cartesian coordinate space have been presented in Figures from 15 to 22. These figures contain the start and end positions of the Own and Target vessels with respect to navigational trajectories. The initial vessel speed condition is Vo/Va = 0.5 and initial course of the own vessel is

Advanced Ship Design for Pollution Prevention, C. Guedes Soares and J. Parunov (Eds.), Taylor & Francis Group, London, UK, 2010, ISBN 978-0-415-58477-7, pp 205-216. (In Proc. Of the International Workshop "Advanced Ship Design for Pollution Prevention", Split, Croatia, Nov. 23-24, 2009)

$\psi o = 0^0$. The star position of the Own vessel (0, 0) and the collision point for both vessels (0, 5) has been considered for all simulations. As noted from the simulations fuzzy logic based DM systems has made proper trajectory for all the collision conditions.

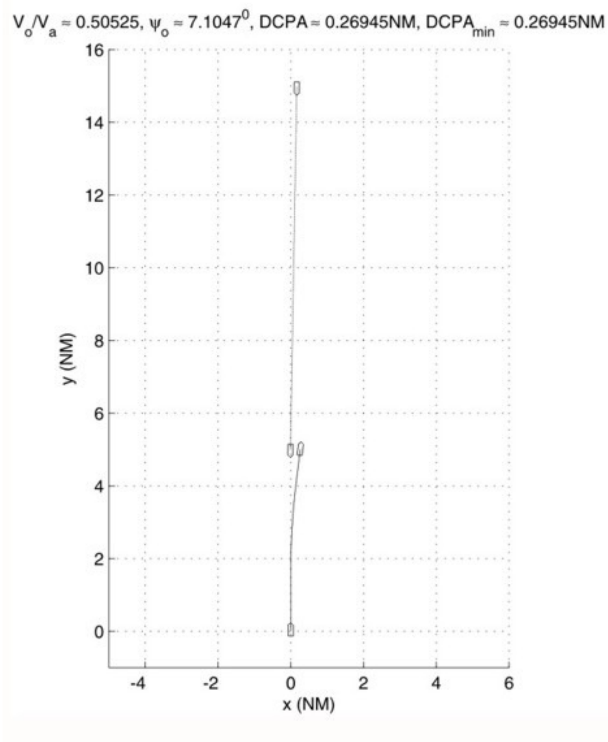

Figure 15: Heading Situation

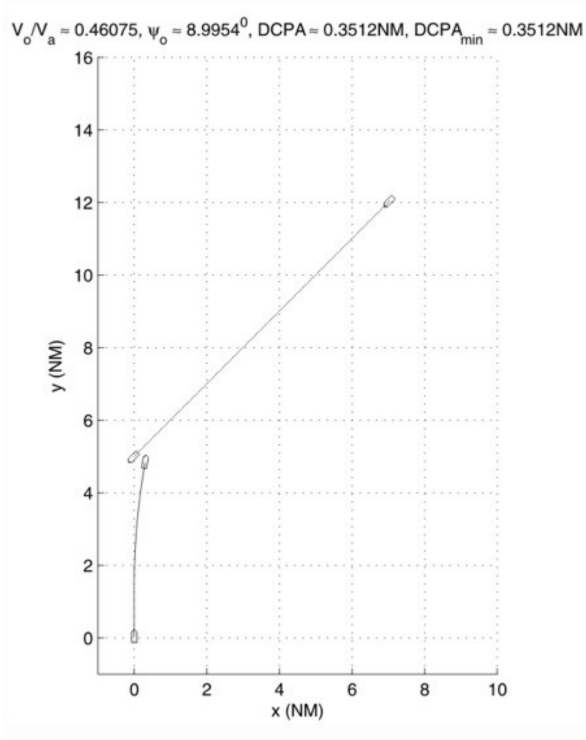

Figure 16: Crossing Situation

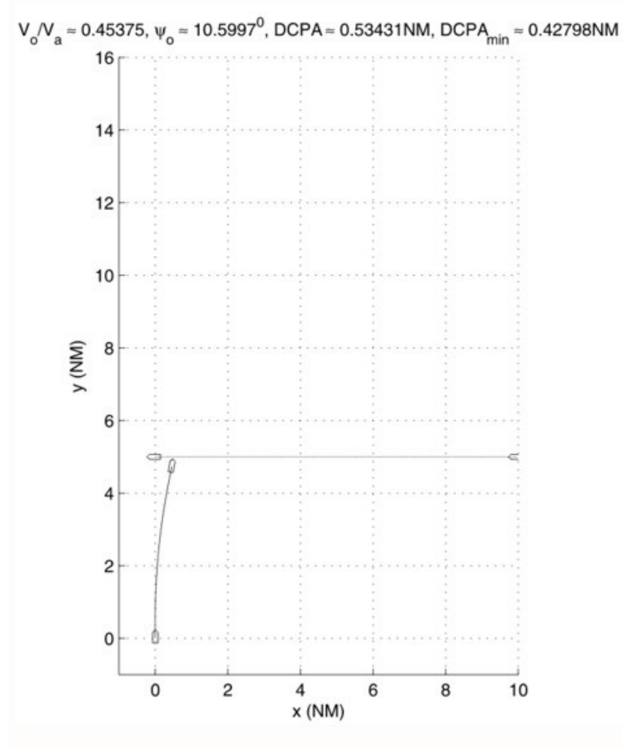

Figure 17: Crossing Situation

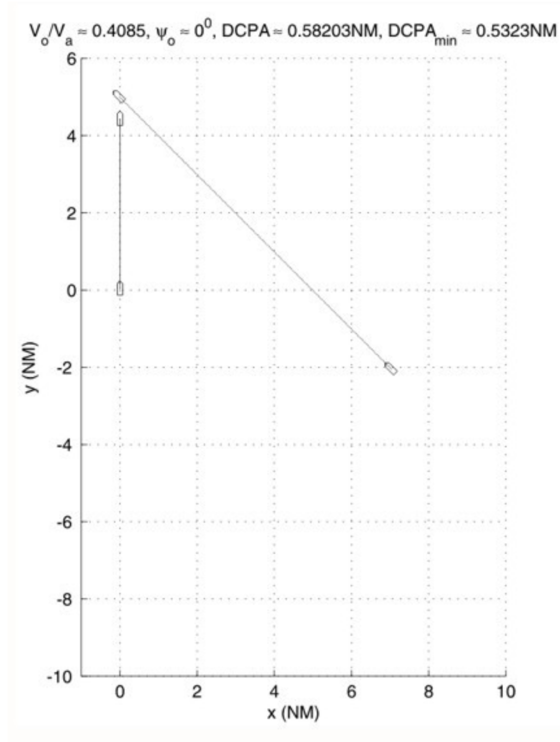

Figure 18: Crossing Situation

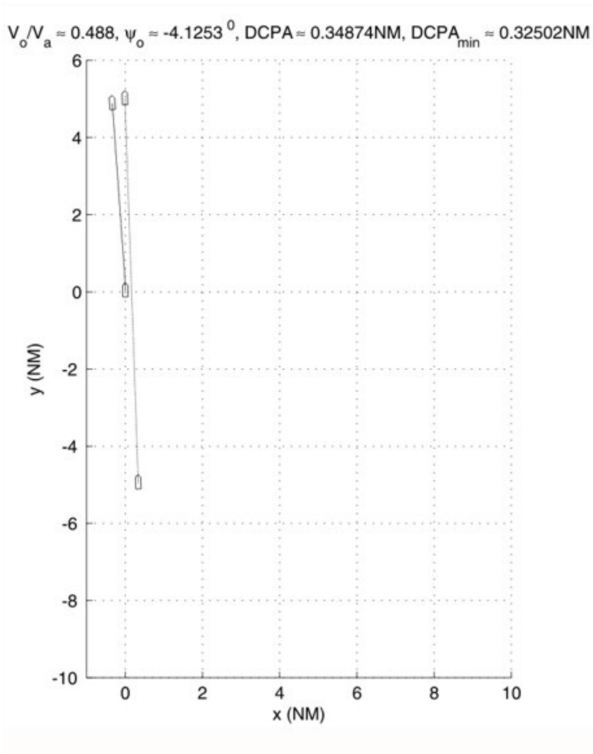

Figure 19: Overtake Situation

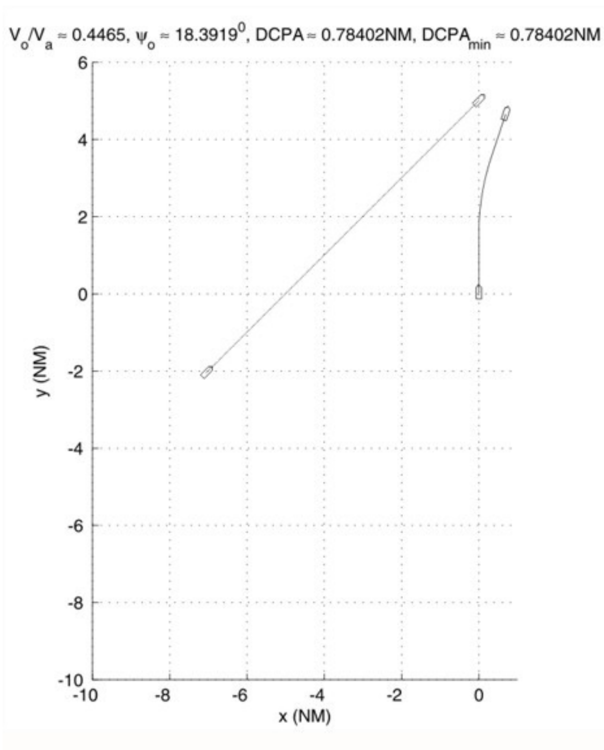

Figure 20: Crossing Situation

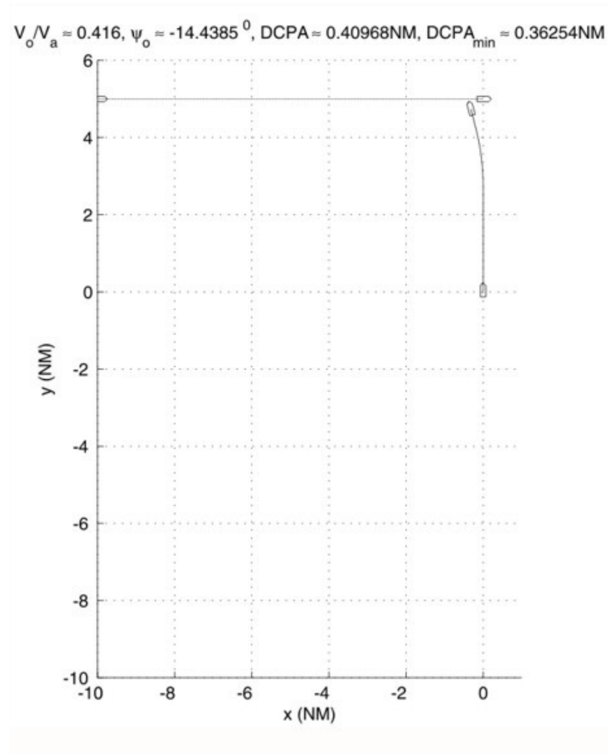

Figure 21: Crossing Situation

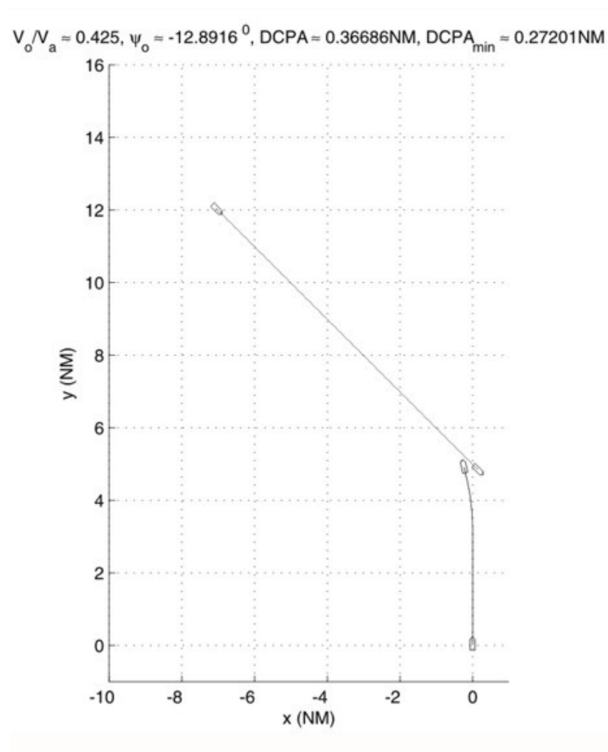

Figure 22: Crossing Situation

5 CONCLUSION

An overall discussion about inclusion of collision avoidance in AGN systems has been presented. In the case study, the decision making process of AGN system that was based on the fuzzy logic and human expert knowledge in ocean navigation is introduced. As observed, the DM system was able to overcome collision conditions by fuzzy logic based decision making process. Furthermore the DM system has taken proper maneuvers to avoid close-quarter situation during the ocean navigation where the collision risk is high. Therefore the DM system would not have to take quick decisions based on inadequate information and time as human decisions.

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