The Fuzzy Properties of the Ship Control in Collision Situations

Mostefa Mohamed-Seghir
Department of Ship Automation, Gdynia Maritime University
83 Morska str. 81-225, Gdynia, Poland
m.mohamed-seghir@we.am.gdynia.pl

***Abstract* - This article focuses on fuzzy set theory as intelligent tools for navigator's decision-making to improve the safety of marine vessels in collision situations. A lot of progress has been made, especially in the field of artificial intelligence. The paper goal is to develop a decision support system based on artificial intelligence to determine a ship's trajectory in a collision situation. In this present work ship trajectory optimization in collision situations is presented as multistage decision-making in a fuzzy environment. The navigator's subjective assessment in making a decision are taken under consideration in the process model and it shows the modified membership function of constraints.**

Keywords— Artificial intelligence, decision-making, ship trajectory, collision situations.

I. Introduction

In the last decades the dynamics of computerization has grown very rapidly. Thanks to this, we have the ability to use entire computer systems on ships to ensure safety and improve the living conditions of the crew [1, 3, 6, 7, 16, 19]. The research for novel effective methods to avoidance ship collisions has become very important with the increasing size, speed and number of ships participating in sea transport. Since when were debut the application of the ARPA (Automatic Radar Plotting Aid) the safety of maritime navigation has increased. Information from DSS (Decision support Systems) can be used by the anti-collision system, whose main task, at the time of a dangerous situation, is to determine the proper passage path for the ship. The designated trajectory is not only to be fully secure but also optimal so as not to allow for big road loss. The basic element of the anti-collision system is its software based on modern ship control methods [11, 13, 14].

A new trend in contemporary ship control includes the process of automating the selection of the optimal collision avoidance maneuver or optimal safe ship trajectory, based on information obtained from the collision prevention system [1, 8, 9, 10, 13, 14]. This paper discusses in detail the ship optimal position determining process, involving stages of ship trajectory, based on the kinematic model. It is assumed that the motion of targets is uniform and occurs as a straight line. Due to the fuzziness of the process, individual approach of a particular officer-navigator, the decision-making process is also, to some extent, an ambiguous evaluation of the safe approach distance and safe time to avoid collision manoeuvre [14]. Moreover, it is assumed that an optimal safe trajectory in a collision situation is a multistage decision-making process in a fuzzy environment this idea is shown in figure (Fig 1) [1, 21, 22].

II. The Kinematic Model of the Process

In order to describe the safe ship trajectory, the movement of a ship returning by its rudder in deep water was described.

To evaluate the dynamic properties of the ship used parameters transfer function or the advance time t_w and maximum angular speed ω. Manoeuvre parameters are selected on the basis of the dynamics of the ship under operating conditions. They are dependent on the angle of rudder, speed, the rudder angle and load and the ambient conditions (Fig 2).

Usually, maritime manoeuvre of the ship in collision situation consists of two phases:

1. tracing targets base on the CPA and TCPA to assess the risk of collision situation,
2. anti-collision manoeuvre according to COLREG, where the determination of a safe trajectory of the ship can be reduced to the issue of multi-stage decision-making in a fuzzy environment.

The quality of the decision is assessed on the basis of fuzzy decision, which is a aggregation of fuzzy objectives and fuzzy environment.

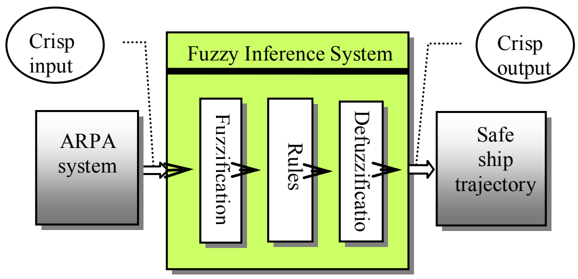

Fig 1. The block diagram of decision support system based on fuzzy set theory.

The task of the anti-collision system is the processing of radar signals and generate traffic information relative and real of objects traced . The signal processing circuit performs the processing of initial and secondary. In the first process is done the processing radar signals which are synchronized with the rotation of the radar antenna. In this process they are

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determined polar coordinates: bearing and the distance between the ship and objects (Fig 2). In the process of processing the secondary performs a correlation coordinates of the position of objects in successive rotations of radar antennas, parameters estimation position of the movement and the approximation of the detected objects relative to the ship.

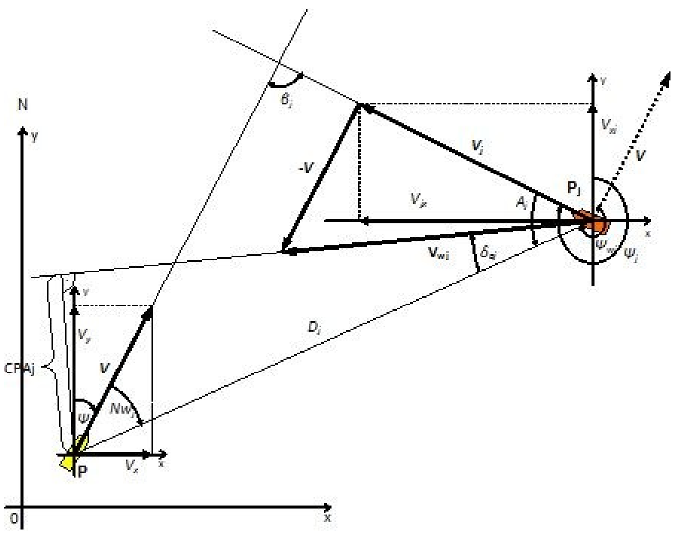

Fig 2. The ship passing situation with j-th target in a rectangular coordinate system. D_j – distance between ship and j-target, CPA_j - the closest point of approach, V – ship speed, V_j – j-th object speed, ψ – ship course, ψ_j – j-th object course, N_j –bearing of the j-th object, V_w – the relative speed of j-th object, ψ_w – the relative course of j-th object.

The model of safe ship trajectory can be represented by the state equation [2, 12, 14]:

$$f(\boldsymbol{X}, \boldsymbol{S}) \rightarrow \boldsymbol{X} \mathrm{x} \boldsymbol{S} \tag{1}$$

$$X_{k+1} = f(X_k, S_k), \quad k = 1, 2, ..., N \tag{2}$$

where:

$X_{k+1}, X_k \in \boldsymbol{X} = \{a_0, a_1, ..., a_{p-1}, a_p, a_{p+1}, ..., a_N\}$ - set of real ship position coordinates

$S_k \in \boldsymbol{U} = \{c_0, c_1, ..., c_m\}$ - control set

The process comes to an end when a ship attains back points (final points) called the final states $\boldsymbol{W} \subset \boldsymbol{X}$ [1, 2].

$$\boldsymbol{W} = \{a_{p+1}, a_{p+2}, a_n\} \tag{3}$$

The set of final states must satisfy this condition:

$$c_{opt}\,,\ \mu_R \leq \mu_{Rsafe}, \tag{4}$$

where:

$c_{opt} = (\psi_{opt}\,, V_{opt})$ - optimal control,

μ_R - membership function of fuzzy set collision risk.

A. Membership Function of the Fuzzy Collision Risk

Ships that participate in a collision situation should be sorted according to the degree of danger. It is used an indicator of collision risk. This indicator is defined by referring to the current approximation situation, described by the *CPA* and *TCPA* parameters, to a safe situation predetermined by a safe proximity distance and the safe time required to avoid a collision avoidance manoeuvre. The ship's domain is treated as a collision risk assessment by many scientists [4, 5, 10, 17]. The membership function of the fuzzy collision risk was used in this work as collision risk assessment [1, 2, 12]

$$\mu_R(k,j) = \frac{1}{exp(\lambda_{RD}(k,j)CPA_j^{\,2} + \lambda_{RT}(k,j)TCPA_j^{\,2})} \tag{5}$$

B. Membership Function of the Fuzzy Goal

Anti-collision manoeuvre, that is, action taken to avoid collision with another ship, should be done in such a way that two objects have passed a safe distance. The effectiveness of the manoeuvre should be monitored until the other ship has passed and departed. A variety of safety assessments made by navigators can be described as a membership function of the fuzzy goal, allowing for a subjective assessment:

$$\mu_G(k, j) = 1 - \frac{1}{exp(\lambda_D(k, j)CPA_j^{\,2})} \tag{6}$$

C. Membership Function of the Fuzzy Constraints

Each anti-collision manoeuvre causes a change in the course navigator's intent. The consequence of course change is the length of the ship's path, resulting in additional waste of time and fuel. The task of the navigator is to perform the safe operation of passing a foreign object at a safe distance with the optimum trajectory to minimize the loss. While, the membership function of the fuzzy constraints can be defined as constraints of manoeuvre at each stage:

$$\mu_C(k) = \frac{1}{\exp(\lambda_C(\mathrm{k})(V\cos\psi(k) - V\cos\psi(k-1) + L)t_k^{\,2})} \tag{7}$$

L - distance from the primary course,

$t_k^{\,2}$ - time function in minutes passed from stage 0 to stage k.

$$L = \left| r(k) + tg(V\cos\psi(k) - V\cos\psi(k-1)) * \Delta d \right| \tag{8}$$

$r(k)$ - distance from primary course in given state x_k,

Δd - distance between successive stages of the primary course.

Increasing the angular angle causes that a membership function of the fuzzy constraints to be bound to the zero, so that continuously increasing the loss of the path of the ship. Loss of road will not occur when $\mu_C(k) = 1$, so when the original course of the ship remains unchanged [22].

The fuzzy set decision is determined as the fuzzy set $\boldsymbol{D} \subseteq \boldsymbol{X}x\boldsymbol{S}$. It is a result of an operation "*" of the fuzzy set of a goal and fuzzy set of constraints:

$$\boldsymbol{D} = \boldsymbol{G} * \boldsymbol{C}, \tag{9}$$

$$\mu_D(.,.) = \mu_C(.,.) * \mu_G(.,.) \tag{10}$$

Where:

λ_{RD}, λ_{RT}, λ_D, λ_C - navigator's subjective parameters,
CPA - the Closest Point of Approach,
TCPA - the Time to Closest Point of Approach,
V - ship speed,
ψ - ship course.

III. THE FUZZY PROPERTIES PROCESS CONTROL SHIP

Identifying characteristics of fuzzy process, reflecting the determination of the safe ship trajectory in collision situation, you cannot do without specifying the parameters that characterize the subjective decisions navigators taken in a given situation. The types of decision were chosen, used in a multi-stage decision-making on the basis of a completed empirical research among navigators.

Examine each navigational situation that may occur during the trip, it is not possible. However, to describe a few basic navigational situation, then it gives you the ability to treat any situation as an accident a few basic situation. For this reason, it is important to examine all the basic situation of navigation. Situations can be divided depending on the angle of the exchange rate, the difference courses, the ship's speed, the speed of the object, the dynamic properties of the vessel and visibility.

Among all the meetings ships awarded twelve categories. Plane around the ship can be divided into sectors according to the angle of the exchange rate (Fig 3). This helps in classifying all basic types of meetings of ships on the basis of the exchange rate and the difference courses.

Given the angle division into sectors can be distinguished twelve categories of meetings of ships Depending on this, after which the side of the ship the meted object is located Table 1.

Above, to describe a membership functions of fuzzy set, The λ_{RD}, λ_{RT}, λ_D, λ_C coefficients have been used to characterize the subjective assessment of ship safety, road loss, and also in determining the membership function of the fuzzy collision risk. The values of these coefficients were determined on the basis of empirical research among navigators. Presented to the navigators characteristic collision situations as simulations. These simulations were based on earlier ship traffic research.

For example the values of the membership function of the fuzzy collision risk should be given for each situation, for each type of ship and with good and limited visibility. The collision risk function can take values from 0 to 1 where $\mu_R(k,j) = 0$ is total safety and $\mu_R(k,j) = 1$ full danger when encountering targets.

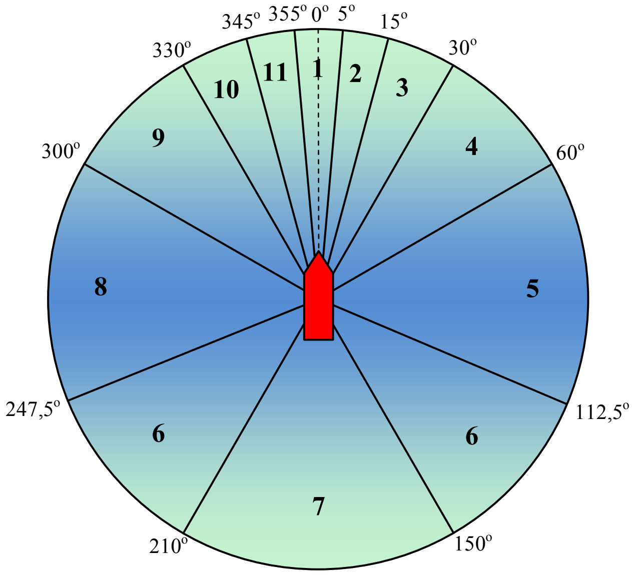

Fig 3. Division of ship's c ourse angle into sectors.

TABLE I. CATEGORIES OF SHIP ENCOUNTER TYPES DEPENDING ON THE COURSE ANGLE AND DIFFERENCE OF COURSES

Meeting type	Course angle [°]	Difference of courses [°]	Description of the type of ship encounter
1	355 – 005	170 - 190	Ships going straight ahead
2	005 – 015	185 - 210	Crossing at a small angle, target on the right side of the ship.
3	015 – 030	195 - 240	Crossing, target on the right side of the ship.
4	030 – 060	210 - 300	Crossing at a large angle, target on the right side of the ship.
5	060 – 112.5	240 - 360	Convergent crossing target on the right side of the ship.
6	112.5 –150 210 – 247.5	300 - 360 000 - 060	Overtaking ships at convergent courses. The ship is overtaken.
7	150 – 210	330 - 030	Overtaking ships at parallel courses. The ship is overtaken.
8	247.5 - 300	000 - 120	Convergent intersection, target on the left side of the ship.
9	300 – 330	060 - 150	Crossing at a large angle, target on the left side of the ship.
10	330 – 345	120 - 165	Crossing, target on the left side of the ship.
11	345 – 355	159 - 175	Crossing at a small angle, target on the left side of the ship.
12	330 – 360 000 – 030	000 - 030 330 - 360	Overtaking ships at parallel courses. The ship is overtaken

IV. Algorithm and Simulation Research

To solve the problem presented above, we use the following algorithm. Applied algorithm takes into consideration a ship's dynamics and requirements of International Regulations for Preventing Collisions at Sea (Fig 4).

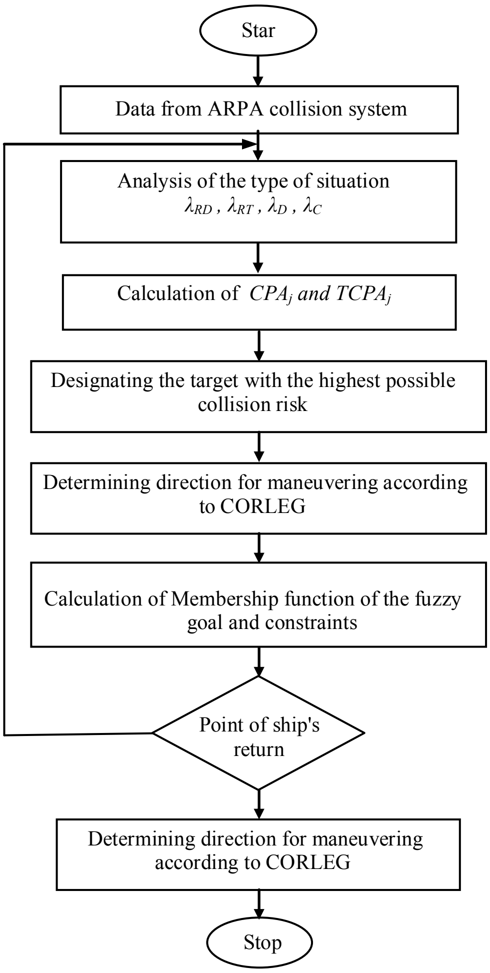

Fig 4. Block diagram of the algorithm for determining the optimal safe ship's trajectory in a fuzzy environment

In order to verify the effectiveness of the proposed collision avoidance method, in a Matlab is performed a simulation for selected navigational situations taking into account the law of the sea COLREG. The aim of the simulation research is to determine the optimal safe ship trajectory in collision situations, to evaluate method to solve the problem formulated in this work by using fuzzy set theory as a multi-stage decision-making process in the fuzzy environment.

This representative navigational situations are simulated as shown in figure 5, 6 and 7.

A. The Ship Collision Situation of Passing for Moving Ships.

Table II and figure 5 relate to the simulation of a safe ship trajectory when passing with three moving targets. The table and figure show the input data of the targets and its own ship, where the manoeuvring parameters are. t_w = 6 [min] (the advance time), ω = 40 [rpm] (maximum angular speed) and a graphical representation of the optimal trajectory of a safe ship in real traffic.

TABLE II. Ship Coordinates and Targets Coordinates. (3 targets).

Ship coordinates				
Position [X Y]	***Course ψ [°]***	***Speed V[kn]***	***Visibility***	
0.0, 0.0	0	12	good/	
Targets coordinates				
Target.	***N_j [°]***	***D_j [nm]***	***ψ_j [°]***	***V_j [kn]***
1	45	3	220	14
2	310	3	90	16
3	200	4	35	18

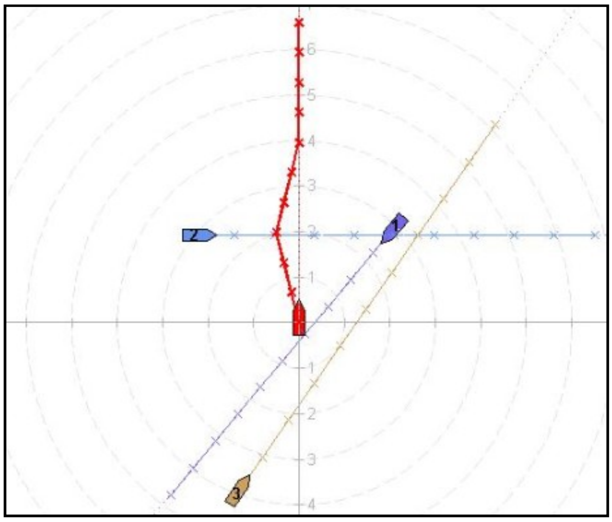

Fig 5. Safe ship's trajectory when passing with three moving targets.

The above situation shows the behaviour of the algorithm for the appearance of two dangerous objects. The ship makes a manoeuvre (ψ_0= 346^0) in relation to the ship number 2 because there is a ship number 1 on the right side which is also dangerous. The ship sustains this course until the passing of the ship number 2 by the stern. Own ship maintains this course until the moment to passing with the ship number 2 behind the stern. When the situation becomes safe, the ship returns to the assigned course.

B. The Ship Collision Situation of Passing Seven Moving Ships and Two Fixed Objects.

Table III and figure 6 relate to the simulation of a safe ship trajectory when own ship passing with six moving targets and two fixed targets..

TABLE III. SHIP COORDINATES AND TARGETS COORDINATES (8 TARGETS).

Ship coordinates				
Position [X Y]	***Course ψ [°]***	***Speed V[kn]***	***Visibility***	
0.0, 0.0	0.0	12.0	good	
Targets coordinates				
Target	***N_j [°]***	***D_j [nm]***	***ψ_j [°]***	***V_j [kn]***
1	260	5	120	18
2	25	6	90	20
3	280	4	75	0
4	40	6	230	17
5	300	5	75	16
6	110	5	200	20
7	55	6	195	0
8	330	6	120	21

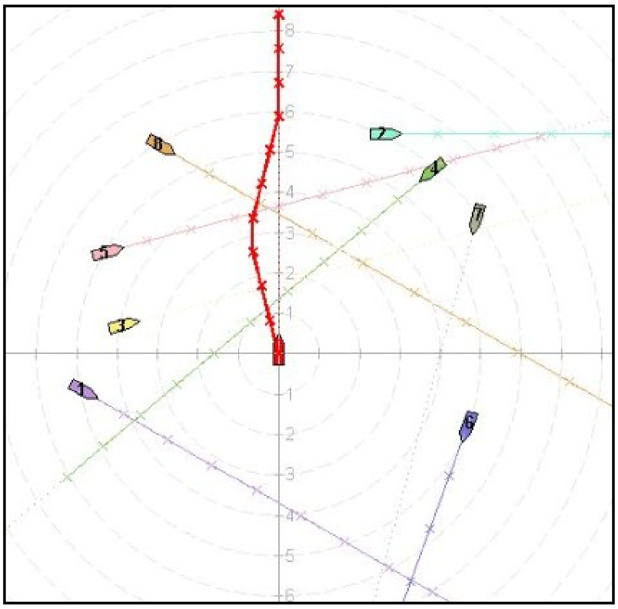

Fig 6. Safe ship's trajectory when passing with six moving targets and two fixed targets.

C. *The Ship Collision Situation of Passing Eleven Moving Ships and Two Fixed Objects.*

Table IV and figure 7 relate to the simulation of a safe ship trajectory when own ship passing with ten moving targets and two fixed targets..

TABLE IV. SHIP COORDINATES AND TARGETS COORDINATES (12 TARGETS).

Ship coordinates				
Position [X Y]	***Course ψ [°]***	***Speed V[kn]***	***Visibility***	
0.0, 0.0	0.0	10.0	good	
Targets coordinates				
Target	***N_j [°]***	***D_j [nm]***	***ψ_j [°]***	***V_j [kn]***
1	260	5	120	18
2	25	6	90	20
3	280	4	75	0
4	40	6	230	17
5	0	5	90	16
6	110	5	200	20
7	70	6	195	0
8	330	6	155	10
9	170	7	345	9
10	360	7.5	180	11
11	45	9	270	12
12	75	5	345	9

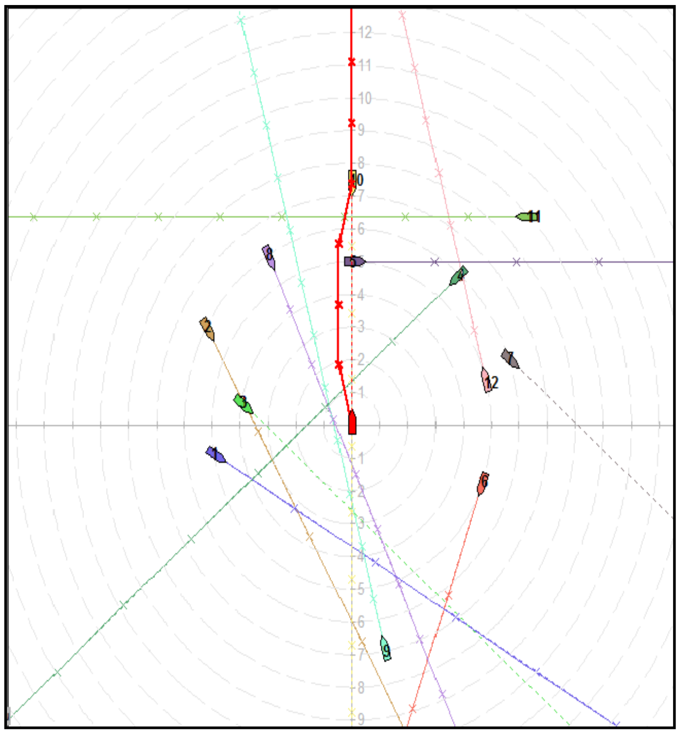

Fig 7. Safe ship's trajectory when passing with ten moving targets and two fixed targets.

CONCLUSIONS

An analysis of the method of determining the safe ship trajectory in collision situations in a environment allows the following conclusions to be drawn:

- The model developed to reflect the real process of safe navigation of the ship in collision situations, consisting of a navigation bay, visibility conditions, ship manoeuvrability, object movement and manoeuvre navigator in accordance with COLREG regulations, describes the problem more accurately,
- It is beneficial to use the membership function of the fuzzy collision risk as a criterion for assessing the risk of collision of vessels, taking into account the subjective nature of the navigational manoeuvre,
- The time of calculating the safe trajectory of a ship in collision situations depends on the nature of the situation (the number of objects involved in a given situation).

Summarizing, the application of fuzzy set theory can be found almost everywhere where conventional methods fail, especially in the problems not strictly defined, which is undoubtedly the process of safe control of the ship.

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