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Decision Support System Using Modern Methods of Collision Avoidance in Collision Situations at Sea

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ABSTRACT: Due to the rapid growth of maritime transport, many researchers have developed advanced methods aimed at increasing navigation safety and reducing operating costs, while maintaining compliance with the International Regulations for Preventing Collisions at Sea (COLREGs). Navigating a ship in potential collision situations requires decision-making under conditions of uncertainty and ambiguity – particularly with respect to concepts such as collision risk and safe speed. These concepts are subjective and not clearly defined. In response to these challenges, this paper presents an artificial intelligence-based method that takes into account the navigator's role as a decision-maker. The proposed solution is designed for integration with existing collision avoidance systems. A universal simulator was developed to evaluate the effectiveness of an algorithm for determining a safe ship trajectory in collision situations. Example navigation scenarios were conducted and presented using this simulator.

1 INTRODUCTION

According to classification societies, ship collisions account for several to more than ten percent of total tonnage lost due to incidents such as sinking, fire, mechanical failure, or other breakdowns. As maritime traffic grows—with the speed and size of ships increasing—the need for effective collision avoidance strategies becomes increasingly critical. Ship collisions account for approximately 20% of all maritime accidents. In the 2023 Maritime Accident and Incident Statistics Report (EMSA 2024), the number of incidents, lost ships, and fatalities and injuries was similar or lower than in the previous period. This year, 2,676 maritime accidents and incidents were reported, representing an increase of approximately 1.8% compared to 2022 and a decrease of 2.5% compared to 2021. The number of fatalities at sea was 45 in 2023, 18% less than in 2022, indicating a downward trend. Despite this optimistic downward trend, we are not exempt from searching for the best solutions and methods to improve maritime safety standards. It is estimated that more than half of these collision-related losses could be prevented by more advanced computer systems for managing the safe navigation of ships [1], [2], [3], [4], [5]. Due to the important role that maritime transport plays in global transport, some researchers have conducted a comparative study of sea and rail transport [6].

In recent years, we have observed a very intensive development of artificial intelligence technologies in connection with the control of ships in maritime traffic [7], [8], [9], [10], [11] . Many scientists are trying to improve and introduce new solutions to ship systems responsible for maritime navigation to make the units increasingly safer, more economical, and even, to some extent, autonomous [12] [13]. Implemented automatic control methods can facilitate the work of navigators by performing calculations, estimating the safety of the selected sea route, taking control of the ship and making the most optimal decisions, or supporting the crew in operating the ship's infrastructure during normal operation during a sea voyage [14].

Rapid technological advances and artificial intelligence, along with the growing need to improve maritime safety, have led to the development of devices to assist navigators in their duties. Specialized collision avoidance systems have emerged on the market. These systems provide crucial information on the position, course, speed, and destination of nearby objects, as well as other threats [15], [16], [17], [18]. Modern navigation systems integrate all navigational instruments into a unified information network that offers real-time data on ship motion parameters. These systems significantly support navigators by providing accurate information, enabling them to make informed decisions that ensure safe sea travel. Despite these technological advances, maritime collisions still occur—often due to human error. Many of these accidents could be prevented by developing and implementing advanced computer-assisted methods for safe ship navigation. Artificial intelligence-based techniques offer promising solutions. Improvement of these computational methods can lead to automatic tracking of objects based on data from onboard collision avoidance systems. Such methods can be used to support the navigator's decision-making process or improve the automatic control of the ship during potential collision scenarios [19], [20], [21]. Correct selection of an appropriate evasive maneuver can eliminate human error and significantly improve navigation safety, taking into account the Intergovernmental Maritime Regulations [22], [23] . Taking the above into account, the aim of this work can be defined as developing a method for determining the optimal and safe ship trajectory in multiple-object collision situations. This method should take into account the provisions of the International Maritime Traffic Code (COLREGs), the ship's maneuvering characteristics, and the subjective characteristics of the navigator, who makes the final decision regarding the maneuver. This paper presents a method for determining a ship's optimal course in each phase of a planned route, using a kinematic model that assumes targets move in straight lines at constant speed. Given the uncertainty and subjective judgments of individual navigators, decisions about maintaining a safe distance and maneuvering to avoid collisions are inherently inaccurate. To address this issue, this study proposes a fuzzy dynamic programming approach for calculating safe ship trajectories in potential collision scenarios [24], [25], [26], [26] (Figure 1).

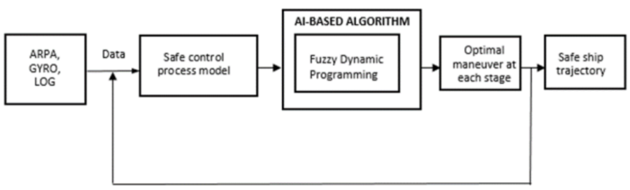

Figure 1. Block diagram of decision support system in a fuzzy environment

2 PROCESS MODEL

To describe a ship's safe trajectory, the ship's motion returning to the helm in deep water was described. The ship's dynamic properties were assessed using the transition function, i.e., the lead time tw and the maximum angular velocity ◎. The maneuver parameters were selected based on the ship's dynamics in operational conditions. They depend on the rudder angle, speed, rudder angle, load, and environmental conditions (Figure 2).

Typically, a ship's maritime maneuver in a collision situation consists of two phases:

1. target tracking based on CPA and TCPA to assess collision risk,
2. anti-collision maneuver in accordance with COLREGs, in which determining the ship's safe trajectory can be reduced to multi-stage decision-making in a fuzzy environment.

The quality of the decision is assessed based on the fuzzy decision, which is an aggregation of fuzzy targets and the fuzzy environment. The anti-collision system processes radar signals and generates information about the relative and actual motion of tracked objects. The signal processing system performs primary and secondary processing. The first process processes radar signals, which are synchronized with the radar antenna rotation. This process determines the polar coordinates: azimuth and distance between the ship and the objects (Figure 2). The second process correlates the object's position coordinates during subsequent radar antenna rotations, estimates motion parameters, and approximates detected objects relative to the ship.

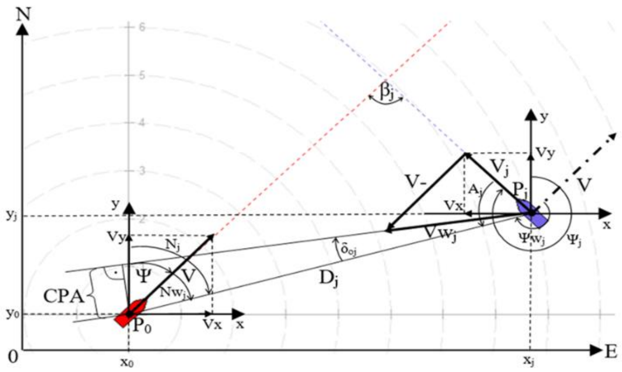

Figure 2. The ship passing situation with j-th target in a rectangular coordinate system

3 SHIP CONTROL PROCESS SYNTHESIS IN A FUZZY ENVIRONMENT

The process of steering a ship in collision situations involves imprecise and poorly defined concepts, such as safe speed, collision risk, and the deadline for taking action to avoid a collision early enough. These terms are subjective and imprecise, and largely depend on the circumstances and navigation conditions. The steering process, characterized by uncertainty, can be represented as a multi-stage model of decision-making and control in a fuzzy environment (Figure 1).

The model of safe ship trajectory can be represented by the state equation

$$X_{k+1} = f\left(X_k, S_k\right), k = 1, 2, \ldots, N \quad (1)$$

where:

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

$S_k = \{c_0, c_1, \ldots, c_m\}$ - control set.

$$\boldsymbol{W_k} = \left\{a_{p+1}, a_{p+2}, a_N\right\} \quad (2)$$

$$\left\{\psi_{opt} = \psi_z, V_{opt} = V_z, \mu_R \leq \mu_{Rsafe}\right\} \quad (3)$$

where:

Ψ_{opt} - optimal corse,

V_{opt} - optimal speed,

μ_R -membership function of fuzzy set collision risk.

To solve the problem formulated above, a method based on an artificial neural network was proposed, as below.

3.1 *Membership function of the fuzzy collision risk*

Ships that participate in a collision situation should be sorted according to the degree of danger [25] . 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 maneuver. The ship's domain is treated as a collision risk assessment by many scientists. The membership function of the fuzzy collision risk was used in this work as collision risk assessment.

$$\mu_R(k, j) = \exp{-^{\left(\lambda_{RD}(k,j)\left(CPA_j\right)^2 + \lambda_{RT}(k,j)\left(TCPA_j\right)^2\right)}} \quad \text{for} \quad TCPA > 0 \quad (4)$$

3.2 *Membership function of the fuzzy goal*

Anti-collision maneuver, 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 maneuver 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.

$$\mu_G(k, j) = 1 - \exp{-^{\left(\lambda_D(k,j)\left(CPA_j\right)^2\right)}} \quad (5)$$

3.3 *Membership function of the fuzzy constraints*

Each anti-collision maneuver 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 maneuver at each stage.

The above functions have been described in detail in other works by the author of this article and are included in the algorithm in the form of pseudocode.

To answer the above problem, a method based on fuzzy dynamic programming is proposed, as presented below.

$$\mu_C(k) = \exp{-^{\left(\lambda_C(k)\left(V\cos\psi(k) - V\cos\psi(k-1)\right)t_k^2\right)}} \quad (6)$$

where:

CPA - Closest Point of Approach,

TCPA - Time to Closest Point of Approach,

λ_{RD}, λ_{RT} - navigator subjectivity parameters in ship collision risk assessment,

λ_D - parameter of the navigator's subjectivity in assessing the ship's safety,

λ_C - parameter of subjectivity of the navigator in assessing the loss of the way.

To identify the properties of a fuzzy process that reflect the process of determining a safe trajectory in collision situations, it is necessary to determine the subjective parameters of the navigator making a decision in a given situation. To this end, empirical studies were conducted to identify and select the types of decisions used in a multi-stage decision-making model. The rationale for using this approach is that humans have a remarkable ability to determine the degree of belonging to a given element without conscious reasoning about how to achieve this degree. Although it is difficult to study every real-world navigational situation, each situation can be treated as the result of several basic situations, based on the principle of superposition. Basic situations can be distinguished based on the angle and difference of course, as well as the ship's speed, the speed of the object, the ship's dynamic properties, and visibility conditions.

3.4 *Fuzzy dynamic programming algorithm*

The aim of this study is also to develop solutions to ensure safe control of the vessel in collision risk situations [18], [19]. This problem is solved using an artificial intelligence based method. In this part of the presented work, a dynamic fuzzy programming algorithm for determining the safe route of own ship at sea is presented. The algorithm is written in the form of pseudocode and presented below. In order to verify the adequacy of the proposed model and the correctness of the algorithm operation, a series of tests were conducted. This part presents one example of a navigation situation in which own ship passes 20 moving and stationary objects. In addition, a sensitivity analysis of the safe ship control process was performed.

Algorithm - Pseudocode

BEGIN
1-Input parameters;
2- Initialization of variables, array and structures;
3- Determine the value of the coefficients λ ;
4- Calculation the CPA, TCPA, and membership functions μ;
5- If safe situation is true go to position 13 else continue;
6- Finding the most dangerous object μ_R

$$\mu_R(k,j) = \exp^{-\left(\lambda_{RD}(k,j)\left(CPA_j\right)^2 + \lambda_{RT}\left(TCPA_j\right)^2\right)} \qquad for \quad TCPA > 0$$

7-Finding the coordinates of your own ships in the last stage *N*;
8- Set the following courses in stage *N*, which are intended to avoid collisions;
9- Selecting the optimal rate at stage N based on membership functions μ_C and μ_G;

$$\mu_C(k) = \exp^{-\left(\lambda_C(k)(V\cos\psi(k) - V\cos\psi(k-1))t_k^2\right)}$$

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

10- Return to the previous stage according to the desired course *N:=N-1*;
11- If *N* = 0 is false go to point 8 else continue ;
12- Designate a safe route based on selected optimal courses at each stage;
13- Calculate the ship coordinates at each stage;
14- Draw a safe route and paths for encountered objects.
END

4 RESULTS OBTAINED WITH THE PROPOSED METHOD

In the initial phase of simulation studies on the optimal and safe ship trajectory, two passing scenarios were analyzed – with both moving and stationary objects – taking into account both good and limited visibility conditions.

In the first scenario, the object was located on the ship's starboard side and moved so that it crossed its course at a 90-degree angle. The second scenario analyzed a situation in which two ships were sailing perpendicular to each other, also in conditions of varying visibility.

The simulations were conducted for a mid-class ship, taking into account applicable COLREG regulations. Due to their simplified nature, the described situations are not presented in detail in this study.

To further verify the accuracy of the applied algorithm, tests were conducted with a larger number of objects participating in potentially conflicting maneuvers. The developed algorithm allows for the analysis of situations with any number of ships. The tests were limited to 60 objects – in line with the maximum number that the ARPA (Automatic Radar Plotting Aid) system can track.

Figure 3 illustrates two example scenarios using the fuzzy dynamic programming algorithm in the safe ship control process:
– A: passing 20 objects (moving and stationary),
– B: passing 60 objects (moving and stationary).

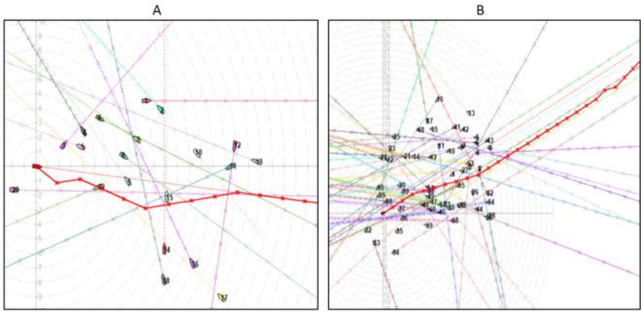

Figure 3. The result of the collision situation in passing with 20 objects (A) and passing 60 objects (B).

As shown in Figure 3A, the anti-collision procedure was carried out safely. After generating a trajectory in 10 steps, the simulation program proposed expanding it to 12 steps. Due to the length of the collision avoidance maneuver, the path was ultimately divided into 12 steps. The most dangerous objects – designated 18, 16, and 17 – were avoided while maintaining safe distances.

The trajectory calculation algorithm allows for a return to the so-called main course (public course), even when intersecting with another trajectory – for example, the course of object 20, which is moving in a straight line. In such a case, the algorithm ensures safe passage of the vessels by maintaining the CPA (Closest Point of Approach) value at 0.75 nautical miles.

Based on the analysis of the simulation test results of the algorithm for calculating a safe trajectory in a fuzzy environment, the following conclusions can be drawn:

The optimal vessel path depends largely on visibility conditions. The poorer the visibility, the sooner or longer the avoidance maneuver takes.

In the presented fuzzy model, the vessel follows a trajectory that minimizes deviation from the main course while allowing for obstacle avoidance at varying distances.

The algorithm assumes a constant collision risk, meaning that navigational decisions are based on the navigator's assessment of the situation, rather than on a fixed minimum distance from the object..

5 SENSITIVITY ANALYSIS OF THE SAFE SHIP CONTROL PROCESS

When constructing utility models for solving control tasks, the choice of model is largely arbitrary, being the result of a trade-off between the required accuracy and the effort needed to collect more experimental data and establish a more accurate model. Since fully accurate models are not used, the problem of the influence of model inaccuracy on the consequences of a decision based on that model becomes of fundamental importance.

5.1 *Sensitivity of the process model*

Sensitivity analysis is the study of the impact of model inaccuracy on the results of applying the resulting control law. Changes in the parameters of the ship control model concern: maximum angular velocity of the turn, time of maneuver progress, subjective navigator coefficients, ship speed, distance between ships and time of maneuver execution. All these parameters appear in the fuzzy set membership functions: "safe maneuver", "start of route" and "collision risk". In order to estimate sensitivity, the sensitivity measure was assumed as the relative increase in the fuzzy set membership function.

5.2 *Control Sensitivity*

Sensitivity tests were performed on two selected navigational situations. In the first situation, the ships' courses intersect at a small angle, and the encountered object is on the port side. In the second situation, the courses intersect at a convergent angle, and the encountered object is on the starboard side. The following quantities were tested:

- the sensitivity of the "collision risk" membership function W_{μ_R},
- the sensitivity of the "safe maneuver" membership function W_{μ_G},
- the sensitivity of the "start of voyage" membership function W_{μ_C}.

The test results are presented as sensitivity curves for each parameter change and input data inaccuracy. Input data errors are expressed as percentages and are the result of the combined measurement error of the navigation equipment and changes in the model parameters.

5.3 *Sensitivity to the accuracy of process status information*

To estimate the sensitivity to the accuracy of information about the process state, the relative increase of the fuzzy set membership function was taken as the sensitivity measure.

$$\mathbf{W}_{KL} = \left| \frac{\mu_K(\mathbf{L}_{rl}) - \mu_K(\mathbf{L}_{pl})}{\mu_K(\mathbf{L}_{pl})} \right| \tag{7}$$

where:
K = 1, 2, 3, …   , l = 1, 2, 3, …, 6
L_{pl} – vector of basic information from the anti-collision system,
$L_{pl} = \{D_j, N_j, \Psi_j, V_j\}$,
L_{rl} – vector of information affected by measurement errors.

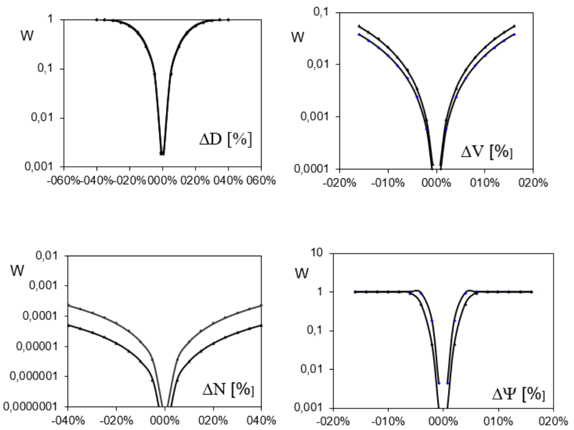

Figure 5. Sensitivity characteristics of the safe ship control process model

5.4 *Sensitivity to changes in process parameters*

To estimate sensitivity to changes in process parameters, the sensitivity measure was assumed to be the relative increase in the fuzzy set membership function.

$$\mathbf{W}_{KL} = \left| \frac{\mu_K(\mathbf{M}_{rl}) - \mu_K(\mathbf{M}_{pl})}{\mu_K(\mathbf{M}_{pl})} \right| \tag{5}$$

where:
K = 1, 2, 3, …   , l = 1, 2, 3, …, 6
M_{pl} – vector of basic information from the anti-collision system,
$M_{pl} = \{ \lambda_D, \lambda_C, \lambda_{RD}, \lambda_{RT} \}$
M_{rl} – vector of information affected by measurement errors.

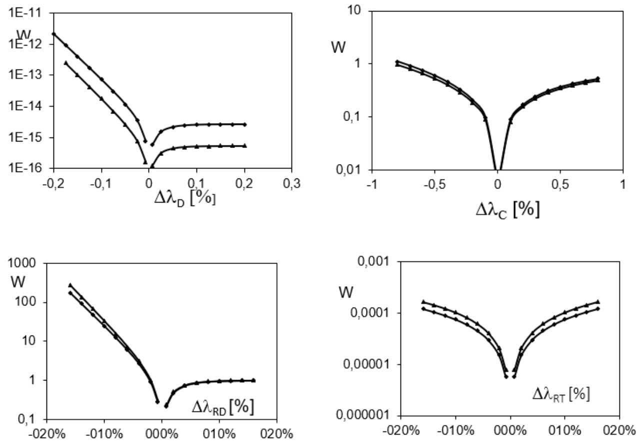

Figure 6. Sensitivity to changes in process parameters.

Sensitivity tests of the ship control process in collision situations in a fuzzy environment showed that:

- the model is not sensitive to changes in the parameters $\lambda_D, \lambda_{RD}, \lambda_{RT}$, when DCPA = 0 or TCPA = 0, it is not sensitive to changes in λ_C, in the absence of maneuvering (V = 0 or   = 0), and also when the navigator is more risky or the object poses a lower collision risk, i.e., $\Delta\lambda_{RD} > 0$, $\Delta\lambda_{RT} > 0$ and $\Delta\lambda_D < 0$, the model is less sensitive to changes in the parameters λ_{RD}, λ_{RT}, and λ_D, and vice versa in the case of $\Delta\lambda_{RD} < 0$, $\Delta\lambda_{RT} < 0$, and $\lambda_D > 0$,
- the sensitivity changes for different signals measurement and parameters characterizing the subjectivity of the navigator's decisions,
- sensitivity varies for different navigational situations,
- sensitivity is in some cases asymmetric relative to the sign of the measurement error.

6 CONCLUSIONS

Analysis of the algorithm's effectiveness in determining an optimal and safe trajectory in collision situations, in a fuzzy logic-based environment, allows for the following conclusions:

The developed model faithfully reproduces the actual conditions for safe ship control in collision situations. It takes into account factors such as water level, visibility conditions, ship maneuverability, the movement of other vessels, and the navigator's maneuvering decisions made in accordance with the provisions of the COLREG convention. This allows the model to more accurately describe the analyzed problem.

Introducing the collision risk set membership function as a criterion for situation assessment is beneficial because it allows for the consideration of subjective factors influencing the navigator's decisions.

The task of determining the optimal ship trajectory can be effectively accomplished using a dynamic programming algorithm.

The algorithm is capable of handling more complex collision scenarios. Although in some cases it may generate maneuvers leading to unnecessary losses (e.g., extending the route), its significant advantage is the automatic return of the ship to its original course after passing the hazard. In summary, the designed algorithm provides a valuable tool to support navigators in making decisions at sea. The simulation results are promising and confirm the algorithm's significant potential for practical application in ensuring safe navigation.

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