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# Modern Method Based on Artificial Intelligence for Safe Control in the Marine Environment

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ABSTRACT: The article presents an approach to formulating a ship control process model in order to solve the problem of determining a safe ship trajectory in collision situations. Fuzzy process properties are included in the model to bring it closer to reality, as in many situations the navigator makes a subjective decision. A special neural network was used to solve the presented problem. This artificial neural network is characterized by minimum and maximum operations when set. In order to confirm the correctness of the operation of the proposed algorithm, the results of the simulations obtained were presented and an discussion was conducted.

## 1 INTRODUCTION

Scientific and technological progress in electronics and related areas of technology as well as the need to increase the safety of sea travel have resulted in the development of devices supporting the work of the navigator. Specialized radar devices appeared on the market in the form of ARPA (Automatic Radar Plotting Aids) anti-collision systems, ECDIS (Electronic Chart Display and Information System), AIS (Automatic Identification System) and many others. They provide information about the location of: detected foreign objects (destination, course and speed), obstacles in the form of shallows or wrecks, danger zones [1]-[4]. Currently, ECDIS systems connect all navigation devices, thus creating an integrated information system about ship motion parameters. They are a great support for the navigator who, on the basis of the information provided by them, makes appropriate decisions related to safe sea travel. Despite the facilities offered by modern devices, ship collisions still occur, often caused by the human factor. Many marine disasters can be prevented by improving and using computer-aided methods for safe ship motion control, such as: differential games, fuzzy control, expert systems, genetic algorithms, neural networks, etc. The improvement of these methods can lead to the automation of the object tracking process based on information obtained on-board anti-collision systems. These algorithms can be used to support the navigator's decisions or as an addition to the automatic control of the ship in a collision situation [5]–[11]. Choosing the right anti-collision manoeuvre at the right moment will eliminate the navigator's error and thus increase the safety of navigation. In recent years, artificial intelligence technology has been rapidly developing in many areas of life, including industry in sea and land transport, etc. [12]-[14]. Many scientists are trying to improve and introduce new solutions to ship systems responsible for sea travel so that vessels become safer, economical and even partially autonomous. The implemented methods of automatic steering are able to facilitate the work of navigators by performing calculations, estimating the safety of the selected sea route, taking control of the ship and making optimal decisions or assisting the crew in servicing the ship's infrastructure during normal sea voyage operation [15] .

The purpose of this study is to develop a method to help the navigator in making decisions in collision situations and to show the possibilities of formulating a model of the process of safe ship control in a fuzzy environment and solving it with the use of artificial intelligence.

## 2 A SIMPLIFIED KINEMATIC MODEL OF THE PROCESS, TAKING INTO ACCOUNT THE DYNAMIC PROPERTIES OF THE SHIP

In the general case, the behaviour of the ship is interpreted as the motion of a rigid body with a specific mass of accompanying water, with six degrees of freedom. For the purposes of ship motion control in collision risk situations, the consideration is limited to the ship motion in the horizontal plane of the movable or stationary coordinate system. The parameters of transmittance or overtaking time $t_w$ and angular velocity $\omega_z$ are used to assess the ship's dynamic properties. These parameters are selected on the basis of ship dynamics tests and depend on the angle of the rudder deflection, speed, degree of loading and external conditions. Neglecting the decrease in speed during course manoeuvring, the kinematic relative motion of the ship, taking into account its dynamic properties after the manoeuvre, can be approximately described by the following equations [16].

$$X_j(t) = X_j + \left(V_j \sin\psi_j - V_0 \sin\psi_0\right)t_w + \\ + \frac{\left(V_j \sin\psi_j - V_0^* \sin\psi_0^*\right)}{\omega_w} tan\left(\frac{\left|\psi_0^* - \psi_0\right|}{2}\right) + \left(V_j \sin\psi_j - V_0^* \sin\psi_0^*\right)t \tag{1}$$

$$Y_j(t) = Y_j + \left(V_j \sin\psi_j - V_0 \sin\psi_0\right)t_w + \\ + \frac{\left(V_j \sin\psi_j - V_0^* \sin\psi_0^*\right)}{\omega_w} tan\left(\frac{\left|\psi_0^* - \psi_0\right|}{2}\right) + \left(V_j \sin\psi_j - V_0^* \sin\psi_0^*\right)t \tag{2}$$

where:
$X_j$, $Y_j$, $X_j(t)$, $Y_j(t)$ –coordinates of the $j$-th object before and after the manoeuvre, respectively,
$V_j$, $\psi_j$ – the speed and course of the $j$-th object, respectively,
$V_0$, $\psi_0$, $V_0^*$, $\psi_0^*$ - speed and course of the vessel before and after the manoeuvre, respectively.

In the case where maneuvering is velocity, the equations of motion take the following form

$$X_j(t) = X_j + \left(V_j \sin\psi_j - V_0 \sin\psi_0\right)T_{on} + \\ + \int_{T_{on}}^{t} \left( V_j \sin\psi_j - \left( V_0^* + \left(V_0 - V_0^*\right) e^{\left(\frac{-t+T_{on}}{T_{kw}}\right)} \right) \sin\psi_0 \right) dt \tag{3}$$

$$Y_j(t) = Y_j + \left(V_j \sin\psi_j - V_0 \sin\psi_0\right)T_{on} + \\ + \int_{T_{on}}^{t} \left( V_j \cos\psi_j - \left( V_0^* + \left(V_0 - V_0^*\right) e^{\left(\frac{-t+T_{on}}{T_{kw}}\right)} \right) \cos\psi_0 \right) dt \tag{4}$$

where: $T_{on}$– delay time; $T_{kw}$ – the time constant of the ship's hull and accompanying water.

Taking into account the presented assumptions, the output values of the model in the form of CPA (Closest Point of Approach) and TCPA (Time to Closest Point of Approach) can be derived from equations (3 and 4). The model described in this way, with the assumptions made, is a mathematical system that will be the basis for solving this problem [17].

## 3 MODEL OF THE PROCESS WITH ITS FUZZY PROPERTIES

In order to obtain a modern anti-collision system, it is necessary to study the process that makes up the navigation environment and manoeuvrability of the ship, as well as the subjectivity of the navigator in making decisions. The process of safe ship control in collision risk situations can be described by a general model of multi-stage decision making in a fuzzy environment. Certain constraints are imposed on all possible decisions, so not all decisions are admissible, therefore the optimal decision is sought among the possible solutions. The ship manoeuvres in accordance with COLREGs (International Regulations for Preventing Collisions at Sea) in relation to the most dangerous object encountered, i.e. The ship's dynamic properties are represented by the angular velocity $\omega_z$ and the overtaking time $t_w$. It is assumed that the controlled process is a deterministic system defined by the equation of state, and The equations of state and output with discrete time are described as follows.

$$\boldsymbol{X}(t+1) = f_x\left(\boldsymbol{X}(t), \boldsymbol{U}(t)\right) \tag{5}$$

$$\boldsymbol{Y}(t+1) = f_y\left(\boldsymbol{Y}(t), \boldsymbol{U}(t)\right) \tag{6}$$

where: ***X, Y, U***- a set of states, a set of outputs and a set of controls, respectively.

Taking into account the above assumptions, the process of determining the ship's safe trajectory is treated as a decision-making process in a fuzzy environment. On the decision set ***U***, a fuzzy set of goals ***G*** and a fuzzy set of constraints ***C*** with appropriate membership functions are defined.

The membership function of the fuzzy goal set defined with values in the range [0,1] is as follows :

$$\mu_G = 1 - \frac{1}{e^{\left(\lambda_d\left(CPA^2\right) + \lambda_t\left(TCPA^2\right)\right)}} \qquad for\ TCPA > 0 \tag{7}$$

However, for $TCPA < 0$, the value of the function equals 1,
where:
$CPA$ - Closest Point of Approach,
$TCPA$ - Time to Closest Point of Approach,
$\lambda_d$, $\lambda_t$ – parameters of the navigator's subjectivity in assessing the ship's safety.

The way loss is presented as a fuzzy constraint whose membership function has the following form:

$$\mu_C = \frac{1}{e^{\left(\lambda_C\left(V_z - V_0\cos\left(\psi_z-\psi_0\right)\right)T_z\right)}} \tag{8}$$

where: $V_z$, $\psi_z$– service speed and set course of the ship, $\lambda_C$ – parameter of subjectivity of the navigator in assessing the loss of the way,
$T_z$ – the time remaining to the turning point of the set course or to reaching the service speed in the case of a speed manoeuvre.

In the presented work, the ship collision risk membership function was formulated in the following form :

$$\mu_R = \frac{1}{e^{\left(\lambda_{rd}\left(CPA^2\right)+\lambda_{rt}\left(TCPA^2\right)\right)}} \qquad for\ TCPA > 0 \tag{9}$$

However, for TCPA <0, the value of the function equals 0,
Where:
$\lambda_{rd}$, $\lambda_{rt}$ – navigator subjectivity parameters in ship collision risk assessment.

The values of the coefficients $\lambda_d$, $\lambda_t$, $\lambda_C$, $\lambda_{rd}$, $\lambda_{rt}$ remained established on the basis of empirical research among a selected group of navigators. Characteristic collision situations were presented to the navigators in the form of simulations, which were determined on the basis of previous studies of ship traffic. For example, the values of the goal's membership function should be given for each situation and type of vessel, and for good and limited visibility. The navigator can choose a value from 0 to 1 at his discretion, 1 is absolute safety, 0 is absolute danger.

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

### 3.1 *Algorithm based on a special neural network*

The aim of this work is to solve the problem of safe ship control in collision conditions [18], [19]. This problem is solved by a method based on neural networks, which solves the problem of dynamic programming in a fuzzy environment. the structure of each artificial neural network depends on the number of layers and the rules of connections between neurons, its size, speed of operation, and above all, the effectiveness of actions that are a tool for solving a given problem depend on it . In this case, the problem is the optimal control of the ship in collision situations, and more precisely, determining its safe trajectory in a blurred environment. To fix the problem, start with the last step and then go back to the previous steps. Referring to dynamic programming, when returning from stage N to stage 0, there are two phases in each stage: minimization and maximization. Such operations can be presented using a special neural network, which, among others, was proposed in work [20]. This neural network is characterized by minimum and maximum operations after a finite set. Taking into account the above information, the algorithm solving the problem of optimal multi-stage control in a fuzzy environment can be described by emulating dynamic programming using a neural network and presented in the form of pseudocode.

Algorithm - Pseudocode

Begin

1 calculation of constraint and goal membership functions at all stages;

2 for all neurons of the maximum type at stage $k$=0 set ; $q_R\left(M_0^j\right)$;

3 for all neurons of the minimum type at stage $k$ set $q_R\left(m_k^i\right)$;

4 for all neurons of the maximum type at stage $k$ set $q_T\left(M_k^j\right)$ ;

5 IF $k$:=$N$ than $k$=$k$+1 go return to position 3, in another case continue

6 set : $k$=1, $j$=1, $i$=1 ;

7 calculation of $q_C\left(m_k^i\right) = q_T\left(m_k^i\right) = f_{N-k}\left(q_R\left(m_k^i\right), q_T\left(M_k^j\right)\right)$ and set $l$=1;

8 IF $q_R\left(M_{k-1}^l\right) = q_T\left(m_k^i\right)$
than set $W\left(M_{k-1}^l, m_k^i\right) = 1$ and calculate
$y\left(m_k^i\right) = \min\left(\mu_C\left(q_R\left(m_k^i\right)\right), \mu_G\left(M_k^j\right), y\left(M_{k-1}^l\right)\right)$;
$u_k\left(M_0^j\right) = \mu_{G^{N-k}}\left(q_R\left(M_0^j\right)\right)$

9 IF $l \neq last\left(M_{k-1}\right)$ than $l$=$l$+1 and return to 8
Else IF $l \neq last\left(m_k\right)$ than $i$=$i$+1 and return to 6
Else IF $j \neq last\left(M_k\right)$ than $j$=$j$+1 and return to 6
Else IF $k \neq N$ than $k$=$k$+1 and return to 6
Else go 10

10 set $t$=0 and $j$=1 and $y\left(M_{N-t}^j\right) = 0$;

11 calculate $y\left(M_{N-t}^j\right) = \max\limits_{i}\left(y\left(m_{N-t}^i\right), y\left(M_{N-t}^j\right)\right)$;

12 IF $i \neq last\left(m_{N-t}\right)$ than $i$=$i$+1 and return to 11
Else IF $j \neq last\left(M_{N-t}\right)$ than $j$=$j$+1 and return to 10
Else IF $t \neq N$ than $t$=$t$+1 return to 10
Else go 13;

13 determining the best solution (way).

End

### 3.2 *The results obtained from the proposed method*

In order to check the adequacy of the proposed model and the correct operation of the algorithm, a number of tests were carried out. This section presents the following three navigation situations.

1. Situation when the ships are heading straight towards each other.
   In Figure 1A, the algorithm determined the anti-collision manoeuvre that allows the object to be passed on the port side. The choice is mainly due to the navigators' subjectivity coefficients, which take into following the recommendations of the COLREG (International Regulations for Preventing Collisions at Sea) [21]–[24]. Then, when the ships are at an equal altitude, the course is leveled, and

after moving away from the foreign object, they return to the original trajectory. Both trajectories were determined correctly and in accordance with COLREG. This is not a complicated collision situation, therefore the determined trajectories differ slightly. However, the influence of weather conditions on determining the safe anti-collision trajectory can be observed, Figure 1B.

The own ship coordinates are as follows : position (x, y) (0,0); Course $45.0^0$ ; speed 10.0 kn.

Table 1. The coordinates of the object in the case of ships heading straight towards each other

| ob. | *Nj* [°] | *Dj* [nm] | Ψ [°] | V [kn] | TCPA [min] | CPA [nm] | μR |
|---|---|---|---|---|---|---|---|
| 1 | 45.0 | 4.0 | 225.0 | 7.0 | 14.12 | 0.00 | 0.997 |

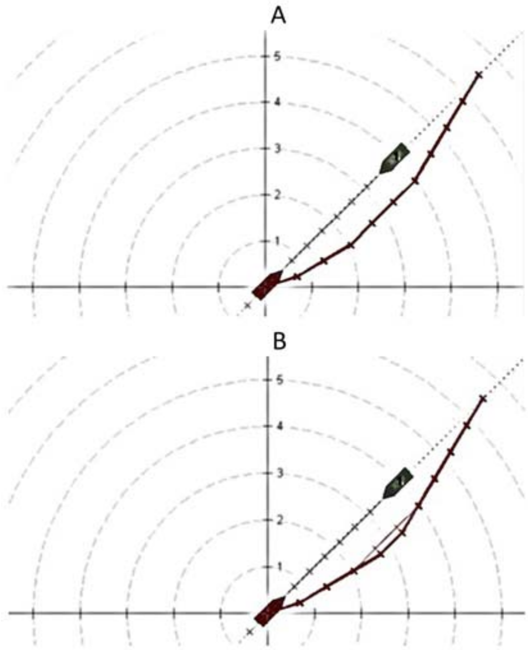


Figure 1. Comparison of trajectories with good and bad visibility in the case of ships heading straight towards each other, A - f good visibility, B - limited visibility.

2. Situation when crossing courses at right angles, the object is on the starboard side.

From Figure 2 it can be concluded that the algorithm determined the optimal trajectory by changing the heading to 59.0°. When the own ship is at the crossover altitude, it returns to its original course. From the report it can be read that the smallest possible approach of ships is 0.66 nm. Thus, the safety condition was met, additionally, the ships passed each other in accordance with the right of sea route.

The own ship coordinates are as follows : position (x, y) (0,0); Course $45.0^0$ ; speed 10.0 kn.

Table 2. The coordinates of the object in the case of crossing courses at right angles, the object on the starboard side

| ob. | *Nj* [°] | *Dj* [nm] | Ψ [°] | V [kn] | TCPA [min] | CPA [nm] | μR |
|---|---|---|---|---|---|---|---|
| 1 | 90.0 | 6.0 | 315.0 | 10.0 | 25.46 | 0.0 | 0.9976 |

3. Situation when crossing courses at right angles, the object is on the starboard side.

Such a situation in which nine objects participated in it, three of which affect the safety of the own ship's voyage. Three of them stand still while the rest move in different directions. Object No. 2 is a direct threat - the value of the collision risk function is 0.5973. Other dangerous objects have a much lower risk and practically do not affect the trajectory of the own ship.

Based on Figure 3, it can be seen that the own ship changed the original trajectory due to the second object with which the collision was most likely. Then the situation was so safe that the own ship returned to its original course and stayed on it until the last stage.

The own ship coordinates are as follows : position (x, y) (0,0); Course $160.0^0$ ; speed 10.0 kn and good visibility.

Table 3. Coordinates of objects when passing 9 objects

| ob. | *Nj* [°] | *Dj* [nm] | Ψ [°] | V [kn] | TCPA [min] | CPA [nm] | μR |
|---|---|---|---|---|---|---|---|
| 1 | 90.0 | 1.600 | 85.0 | 12.7 | -5.17 | 1.11 | 0.0200 |
| 2 | 204.0 | 3.600 | 40.0 | 12.0 | 11.86 | 0.55 | 0.5973 |
| 3 | 190.0 | 3.000 | 86.0 | 12.8 | 10.74 | 1.81 | 0.0035 |
| 4 | 231.0 | 5.000 | 0.0 | 0.0 | 11.23 | 4.73 | 0.0000 |
| 5 | 264.0 | 5.500 | 0.0 | 0.0 | -9.18 | 5.34 | 0.0000 |
| 6 | 216.0 | 4.700 | 0.0 | 0.0 | 18.13 | 3.90 | 0.0000 |
| 7 | 288.0 | 3.600 | 45.0 | 8.8 | -1.35 | 3.58 | 0.0000 |
| 8 | 176.0 | 2.600 | 46.0 | 9.6 | 9.62 | 0.84 | 0.1057 |
| 9 | 203.0 | 5.900 | 40.0 | 7.2 | 24.66 | 1.64 | 0.0099 |

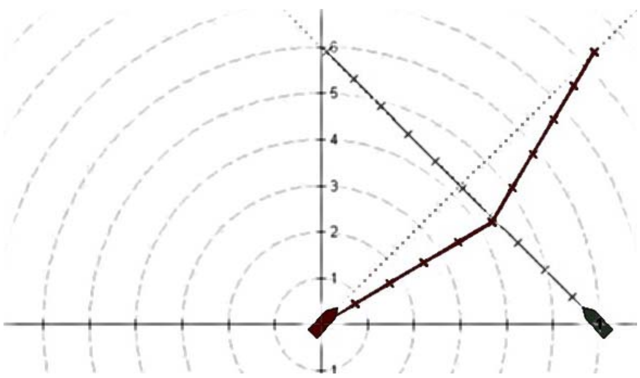

Figure 2. The optimal trajectory for avoiding a dangerous object that crosses the ship's course at right angles.

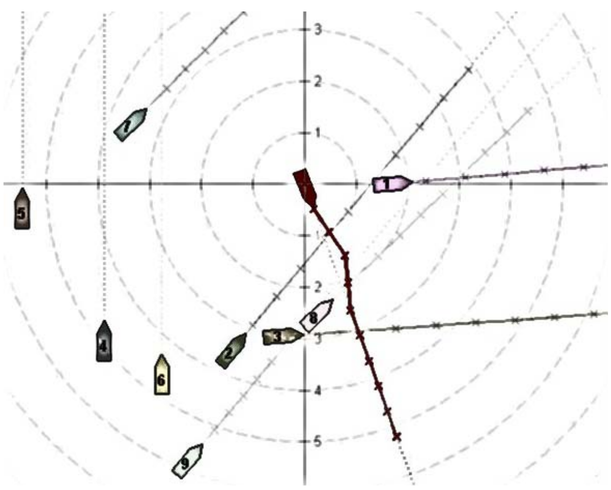

Figure 3. The ship optimal safe trajectory in passing with 9 objects.

For the situation shown in Figure 1A, Table 4 presents a comparison of four algorithms for determining the optimal safe ship in a collision situation in a fuzzy environment. These algorithms are: Branch and bound (BB); Dynamic Programming (DP); Evolutionary Algorithm (EA); Neural Networks (NN). After a brief analysis based on the results included, it can be seen that:

– for the NN algorithm, the calculation time (simulation duration) is much shorter than for other methods and amounts to 1.2 s,
– minimal speed change only in one case for the NN algorithm,
– manoeuvre speed is the fastest for the EA algorithm.

Table 4. Comparison of the results of four algorithms for solving the situation in Figure 1A

| | BB | | DP | | EA | | NN | |
|---|---|---|---|---|---|---|---|---|
| P. | C [°] | S [kn] | C [°] | S [kn] | C [°] | S [kn] | C [°] | S [kn] |
| 1 | 59 | 10 | 67 | 10 | 75 | 10 | 60 | 10.3 |
| 2 | 59 | 10 | 59.6 | 10 | 64 | 10 | 60 | 10.3 |
| 3 | 59 | 10 | 56 | 10 | 59.1 | 10 | 60 | 10.3 |
| 4 | 59 | 10 | 53.7 | 10 | 56 | 10 | 45 | 10 |
| 5 | 59 | 10 | 51.2 | 10 | 53.8 | 10 | 45 | 10 |
| 6 | 31 | 10 | 45 | 10 | 52.6 | 10 | 45 | 10 |
| 7 | 31 | 10 | 30 | 10 | 45 | 10 | 45 | 10 |
| 8 | 31 | 10 | 42 | 10 | 45 | 10 | 30 | 10 |
| 9 | 31 | 10 | 44 | 10 | 45 | 10 | 30 | 10 |
| 10 | 45 | 10 | 45 | 10 | 45 | 10 | 30 | 10 |

C – Course; S – Speed

## 4 CONCLUSIONS

This study was to show the possibilities of formulating a model of the process of safe ship control in a blurred environment and solving it with the use of artificial intelligence. The algorithm is able to solve much more complicated situations, but sometimes there may be manoeuvres in which the path losses are large. For this reason, the algorithm needs to be refined towards a more precise definition of the membership function of the set of constraints. The advantage of the algorithm is that the ship's trajectory returns to its original course if there is no longer any danger. In addition, the result of the presented neural network is selected from many connections, thanks to which the determined trajectory is the best possible to obtain in a given situation. To sum up, the created algorithm can be used as a decision support tool by the navigator in order to maintain safe sea navigation. The obtained simulation results are promising and show the great potential of the algorithm.

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