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# COMPUTER SIMULATION OF A GAME CONTROL MODEL IN A COMPLEX MARITIME TRAFFIC ENVIRONMENT

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**Abstract**
A model of the process of a ship's safe control, moving in the vicinity of many other ships, was formulated, which enables the synthesis of algorithms for safe path planning that is appropriate according to the state of the environment. This state can be mapped using three possible algorithms – the game non-cooperative path, game cooperative path and optimal path. Computer simulation of the algorithms on the example of a real navigation situation recorded in the Baltic Sea of the ship's own movement in the vicinity of another nine moving ships made it possible to assess their effectiveness. When comparing the algorithms, the degree of cooperation of the vessels, the state of visibility at sea and the dynamics of the ship itself determined by the manoeuvring advance time were taken into account. The simulation results of the presented algorithms confirm the effectiveness and good representation of the real state of the traffic environment of many ships. The conclusions from the conducted research can be used to optimize other processes of controlling mobile objects.
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**Key Words:** Traffic Systems, Automatic Control, Optimization Techniques, Game Theory

## 1. INTRODUCTION

### 1.1 The state of knowledge on modelling of mobile objects' control

Modelling and simulation tools are used in many tasks involved in designing and building modern and efficient control systems for mobile objects and autonomous and non-autonomous vehicles.

Thus, Liu et al. [1] constructed and tested the performance of a model of optimal order allocation and unmanned vehicle route planning based on an improved genetic algorithm with load constraints and soft time windows as model constraints. Meanwhile, Filaretov et al. [2] presented a method of significantly increasing the accuracy of technological operations performed with an underwater manipulator using diagnostic observers of dynamic models of the manipulator's electric drive.

The optimization of ship handling on land was proposed by Bebic et al. [3] using a simplified Excel template for queuing theory, inputting data from a computer system of planned ship services. Muthukumaran and Sivaramakrishnan [4] presented a dragonfly metaheuristic algorithm for the planning of the optimal robot path in an environment with obstacles and disturbances. Huang et al. [5] presented a simulation of the control of the path of a space robot using two control subsystems, slow and fast, leading to the active damping of vibrations.

To simulate ship manoeuvers by modelling the operator's actions to the response of other ships, Hoogendoorn et al. [6] used a differential game model. Sutulo et al. [7] presented mathematical models of ship route prediction for use in navigation simulators. The analysis of the simulation of the accuracy of the movement of a bulk carrier in real conditions of its navigation along optimal ship routing was described by Waskito et al. [8]. On the other hand, Nguyen and Tran [9] described the Simplex algorithm for determining the optimal hydrodynamic coefficients, and then a simulation model of the ship's motion in the Matlab software verified it on the basis of experimental data from manoeuvring tests.

### 1.2 The thesis and objectives of this paper

In the literature, there are no works dealing with the modelling and simulation of advanced methods of steering a ship moving in the vicinity of other encountered ships. Therefore, the aim of the article is to demonstrate that it is possible to model and simulate the safe path of a ship moving in a larger group of ships, which will take into account the limitations in decision-making resulting from the ambiguity of the COLREGs manoeuvring rules and environmental disturbances, leading to a game model (see Fig. 1).

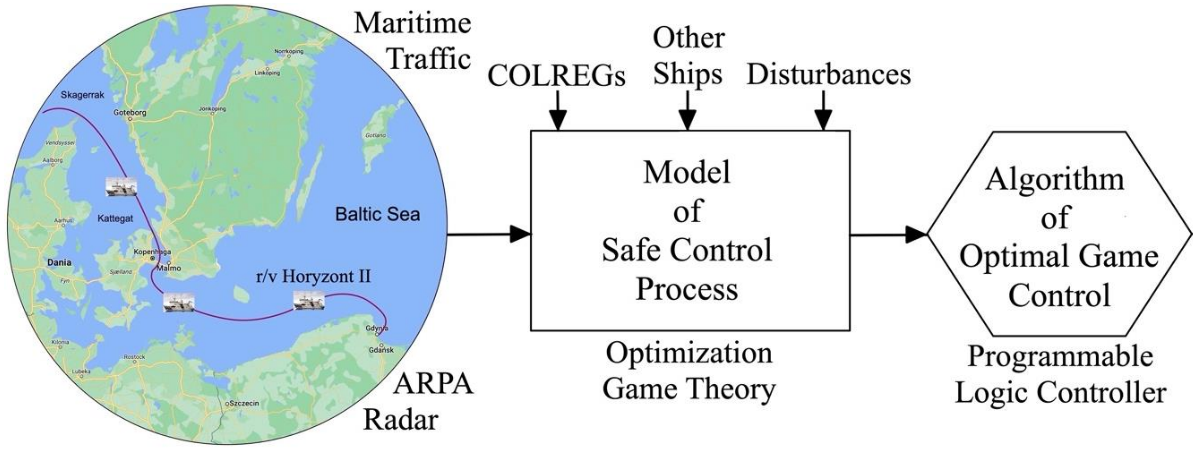


Figure 1: Scheme of safe control system synthesis for ship motion in real maritime environment.

The scientific goal is to synthesize new models of safe control processess and optimal game path algorithms for a ship when passing other ships. The aim of the research is an experimental, comparative analysis of computer simulation tests of control methods at different values of safe passing distance and manoeuvring advance time.

### 1.3 Paper contents

The content of the article is as follows. Section 1 describes the development of modelling and simulation methods for controlling various mobile, autonomous and non-autonomous objects in recent years and formulates the scientific aim of the research. Section 2 presents the model of the safe control process. Section 3 contains a description of the determination algorithms – the game non-cooperative, game cooperative and optimal paths. Section 4 presents the results of the computer simulation of path algorithms on the example of a real navigational situation. Section 5 summarizes this article and outlines future directions for improvement.

## 2. MODELS OF SAFE CONTROL PROCESS

Ships should select their controls from the set of safe manoeuvers $A^m$ in order to pass each other at a given safe distance $D_s$, resulting from the COLREGs rules in good and restricted visibility at sea.

Fig. 2 shows how to determine the $A^m$ set for the following control criteria: $V_{02}$ and $V_{j1}$ – Game Non-Cooperative Path; $V_{02}$ and $V_{j2}$ – Game Cooperative Path; $V_{02}$ and $V_{j0}$ – Optimal Path; $V_0$ – own ship speed; $V_j$ – encountered $j^{th}$ ship; $D_s$ – safe approach distance; $p_k(X_k, Y_k)$ – nearest $k^{th}$ point of own ship's reference course change; ($A^m{}_{01}$, $A^m{}_{02}$) – sets of safe manoeuvers to change own ship's course and speed to port and starboard, respectively; ($A^m{}_{j1}$, $A^m{}_{j2}$) – sets of safe manoeuvers to change $k^{th}$ encountered ship course and speed to port and starboard, respectively.

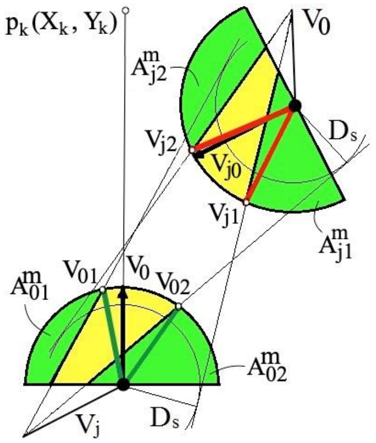


Figure 2: The method of determining the components (green color) of the set $A^m$ of safe manoeuvers.

The task of determining the optimal ship path can be reduced to a linear programming problem [10]. The minimum value of the control objective function $F$ given in a linear form should be determined, representing the shortest time of arrival of our own ship to the nearest turning point $p_k$, corresponding to the maximum component $x_1$ of the velocity $V_0$ for the given direction of motion:

$$\vec{V}_0(V_{0x_1}, V_{0x_2}) = \vec{V}_0(x_1, x_2) \tag{1}$$

$$F(\boldsymbol{x}) = x_1 = \max \tag{2}$$

from the acceptable safe set of manoeuvers $A^m(A^m{}_{01}, A^m{}_{02})$ (see green in Fig. 2):

$$g(\boldsymbol{x}) = a_{1j}x_1 + a_{2j}x_2 \le a_{3j}, \;\; j = 1, 2, \dots, J \tag{3}$$

where the values of coefficients $a_{j1}$, $a_{j2}$ and $a_{j3}$ depend on the values of ship heading angles measured in the ARPA anti-collision radar system [11].

The basic task of optimal and safe ship control formulated in this way can be related to the following three states of the multi-ship traffic environment:

- Ships do not cooperate with each other for safe dispersal, resulting from misinterpretation of COLREGs, loss of navigational data or poor weather conditions;
- Ships cooperate with each other in accordance with the COLREGs rules;
- Our own ship determines its manoeuvring to maintain a safe distance $D_s$ assuming that the encountered ships are moving with a constant course $\psi_j$ and speed $V_j$ [12].

## 3. ALGORITHMS OF OPTIMAL GAME CONTROL

The three states of the ship traffic environment correspond to three different control methods in the form of the following algorithms:

- Game Non-Cooperative Path (GNCP) algorithm, for the control objective function in the form of:

$$F^*_{GNCP}(\boldsymbol{x}) = \max_{V_0^*} \; \min_{V_j} \; \max_{V_0} \; x_1 = t^* \equiv \varepsilon \tag{4}$$

- Game Cooperative Path (GCP) algorithm, with the following control objective function:

$$F^*_{GCP}(\boldsymbol{x}) = \max_{V_0^*} \; \max_{V_j} \; \max_{V_0} \; x_1 = t^* \equiv \varepsilon \tag{5}$$

- Optimal Path (OP) algorithm, with:

$$F^*_{OP}(\boldsymbol{x}) = \max_{V_0} \; x_1 = t^* \equiv \varepsilon \tag{6}$$

where ε is the final deviation of the determined path from the initial direction [13, 14].

Below is the pseudo-code of the general algorithm for determining the ship's safe path, which was written in the Matlab software. The general algorithm includes three specific algorithms corresponding to the described GNCP, GCP and OP procedures.

**Algorithm:** Determination of GNCP – Game Non-Cooperative Path, GCP – Game Cooperative Path and OP - Optimal Path in maritime traffic environment

**BEGIN**
Input and development of initial data
Display of the navigation situation
COLLISION 0
Determination of the collision area
**IF** the other ship is not in collision situation **THEN**
**(**COLLISION = 0, **GOTO** ranking other ships according to the degree of risk collision
and **GOTO** drawing the position of the other ship)
**ELSE** COLLISION = 1
**IF** Dmin>Ds **THEN**
Ranking other ships according to the degree of risk collision
**ELSE** Crash stop
**IF** j ≠ m **THEN**
Determination of the collision area
**ELSE IF** sum of COLLISION not equal 1 **THEN**
**GOTO** OP-Optimal Path calculation (*max* $x_1$)
**IF** OP is min **THEN**
**GOTO** drawing the position of the other ship
**ELSE** - Calculate the parameters for the other ship
- Approximation of the other ship's circle
- Determination of the area of non-acceptable maneuvers
**GOTO** GCP-Game Cooperative Path calculation (*max max max* $x_1$)
**OR** GNCP-Game Non-Cooperative Path calculation (*max min max* $x_1$)
Calculation of the new course
Drawing the position of the other ship
**IF** j ≠ m **THEN**
Return to GCP-Game Cooperative Path calculation
**ELSE** - Approximation of the own ship's circle
- Determination of the area of non-acceptable maneuvers
- Calculation of constraints and goal function
- Calculation of the optimal course to starboard side
- Calculation of the optimal course to left side
- Selection of the course with the least deviation
- Change of speed, if the difference between the selected course is greater by a certain value than the set course
- Plot a new course position
- Set all simplex equations to 0
**GOTO** drawing the position of the other ship
**ELSE** - Draw own ship without collision
- Draw other ship without collision
**IF** j = m **THEN**
Return to draw other ship without collision
**ELSE** Visualize the safe path and calculate the deviation from given road
**END**

## 4. COMPUTER SIMULATION

The GNCP, GCP and OP algorithms were subjected to simulation tests in the Matlab/Simulink software on the example of a real navigational situation recorded on the r/v Horyzont II research-training vessel in the Baltic Sea, during the commencement of the cruise to Spitsbergen (Table I) [15-17].

Table I: Parameters of the navigational situation in the Baltic Sea recorded on research-training vessel r/v Horyzont II.

| **Ship number** | **Distance** (nm) | **Bearing** (deg) | **Speed** (kn) | **Course** (deg) |
|---|---|---|---|---|
| 0 | 0.0 | 0 | 20.0 | 0 |
| 1 | 8.8 | 325 | 14.6 | 91 |
| 2 | 14.3 | 7 | 16.1 | 179 |
| 3 | 7.5 | 12 | 15.9 | 201 |
| 4 | 12.1 | 339 | 0.0 | 0 |
| 5 | 11.9 | 49 | 0.0 | 0 |
| 6 | 5.9 | 224 | 15.1 | 289 |
| 7 | 8.1 | 289 | 11.9 | 301 |
| 8 | 5.2 | 141 | 9.1 | 44 |
| 9 | 13.9 | 29 | 6.3 | 0 |

Fig. 3 shows the velocity vectors $V_0$ of our own ship and nine $J = 9$ other encountered ships' velocity vectors $V_j$ .

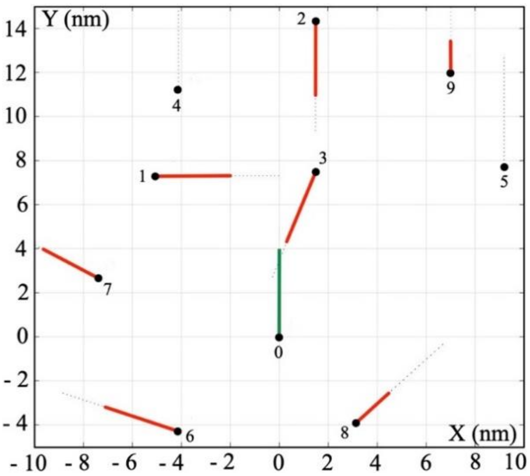


Figure 3: Twelve-minute speed vectors of ships in the navigational situation recorded in the Baltic Sea on the research and training vessel r/v Horyzont II: 0 – own ship; from $j$ = 1 to 9 – other ships encountered.

The results of simulation tests of the GNCP, GCP and OP algorithms for steering a ship in good visibility at sea when $D_s$ = 0.3 nm and in restricted visibility at sea for $D_s$ = 1 nm are shown in Figs. 4, 5 and 6. Such $D_s$ values result from fact that in good visibility at sea, ships can pass at short distances, while in restricted visibility at sea (night, fog, storm) ships pass at greater distances to reduce risk of collision.

The dynamics of ships is presented in the form of manoeuver advance time $T_a$, which consists of the course change time, equal to the setting time $t_s$ the course to the new set value. According to Nise [18], the setting time of an inertial object with a time constant $T$, as the time to reach the setpoint, is equal to the four time constants of the object $t_s = 4\,T$, therefore $T_a = 180$ s [19-28].

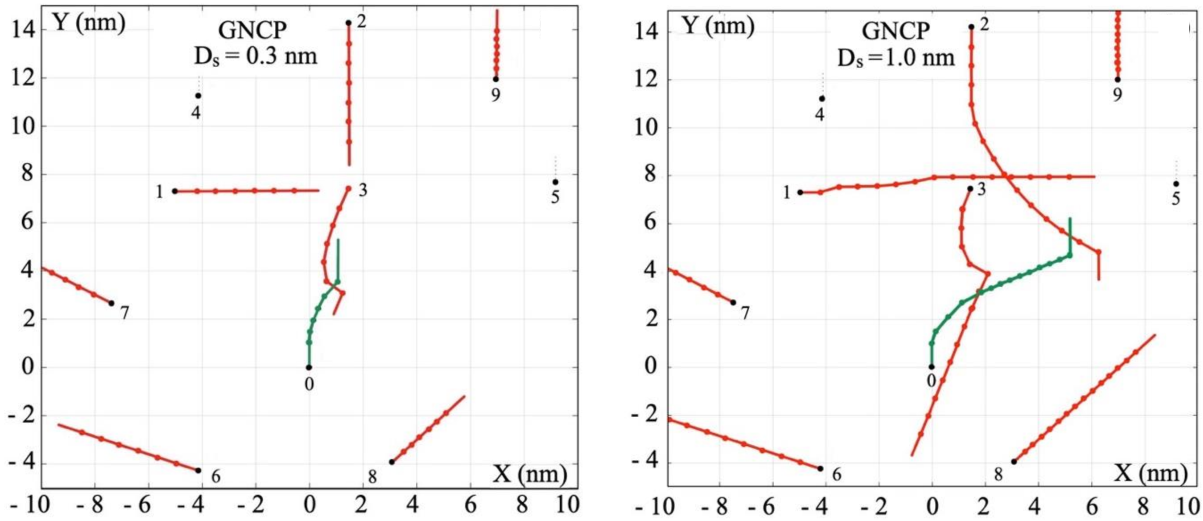


Figure 4: Game Non-Cooperative Path of own ship (green line) in good (left) and restricted (right) visibility at sea; advance time of manoeuvring $T_a$ = 180 s.

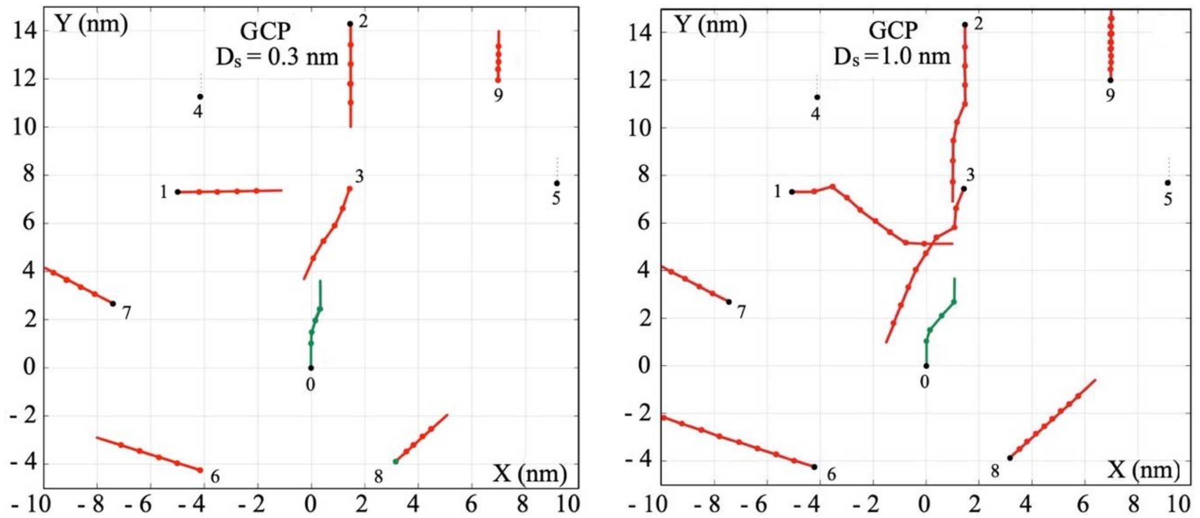


Figure 5: Game Cooperative Path of own ship (green line) in good (left) and restricted (right) visibility at sea; advance time of manoeuvring $T_a$ = 180 s.

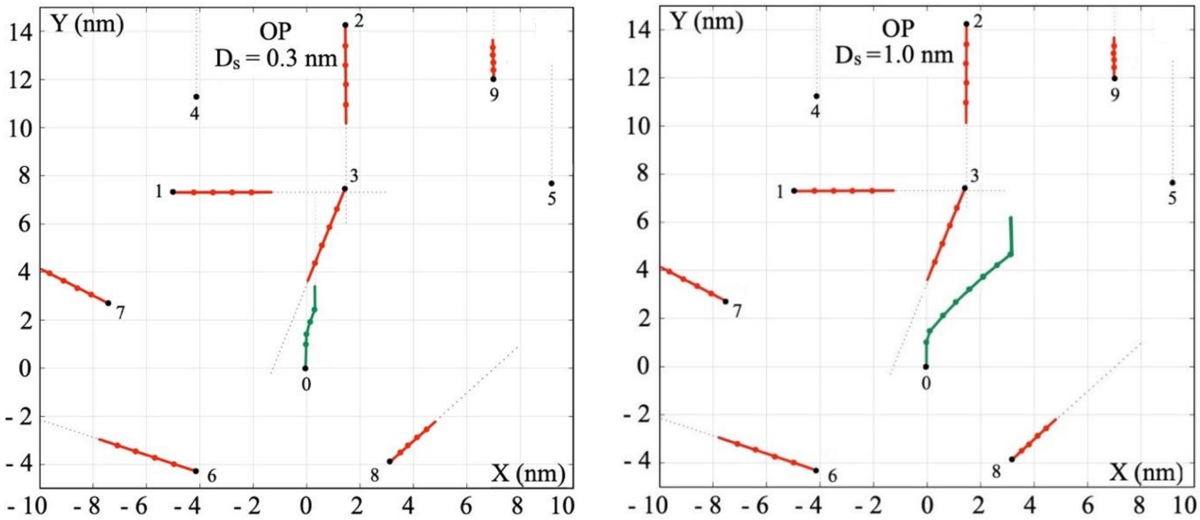


Figure 6: Optimal Path of own ship (green line) in good (left) and restricted (right) visibility at sea; advance time of manoeuvring $T_a$ = 180 s.

A series of simulation studies of the GNCP, GCP and OP algorithms for different values of the safe passing distance $D_s$ and the manoeuvring advance time $T_a$ allowed us to illustrate the variability of the final path deviation ε from the given direction of the ship's motion (Figs. 7, 8 and 9).

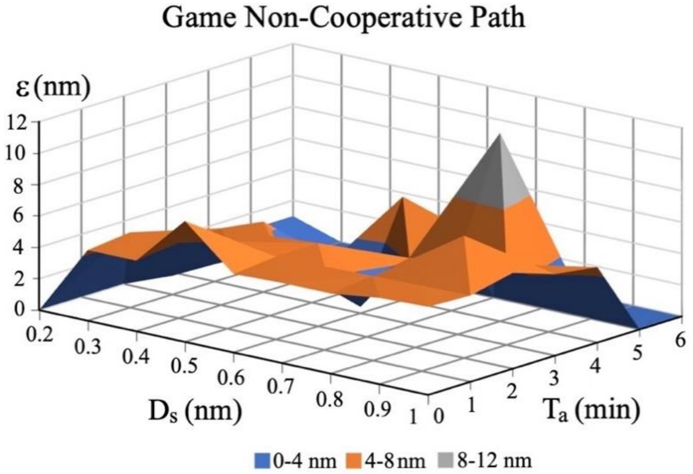


Figure 7: Dependence of the Game Non-Cooperative Path deviation ε on the safe distance $D_s$ and the advance time $T_s$.

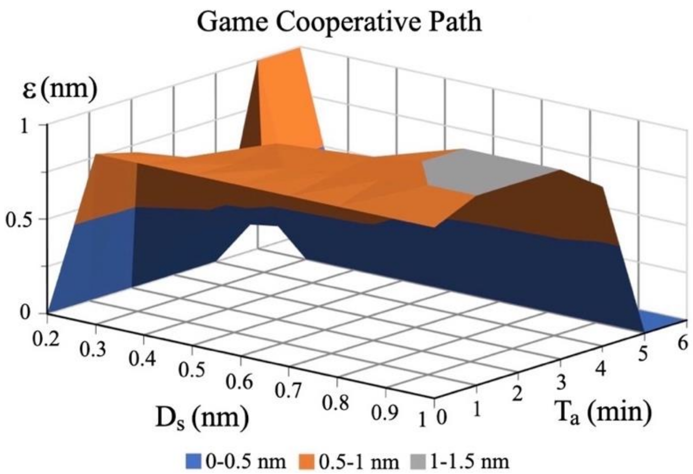


Figure 8: Dependence of the Game Cooperative Path deviation ε on the safe distance $D_s$ and the advance time $T_s$.

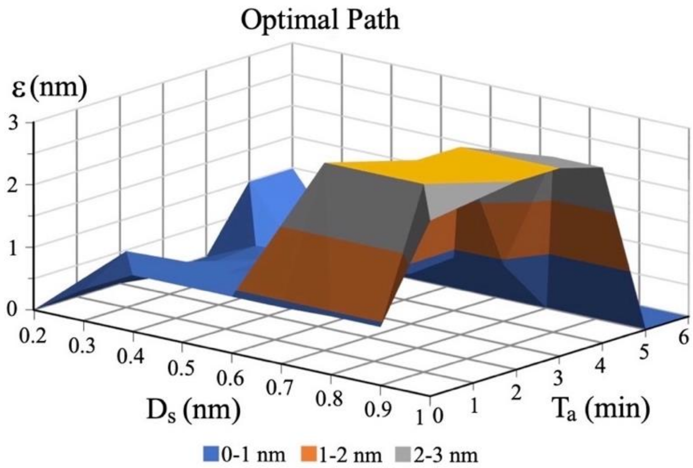


Figure 9: Dependence of the Optimal Path deviation ε on the safe distance $D_s$ and the advance time $T_s$.

Cooperation between ships contributes to a ten-fold decrease in the value of the path ε deviation compared to its abandonment, and a three-fold decrease, assuming that the ships move at constant courses and speeds.

In order to compare the algorithms with each other, Figs. 10 and 11 show separately the dependence of the path deviation ε on the safe distance $D_s$ and on the manoeuvring advance time $T_a$.

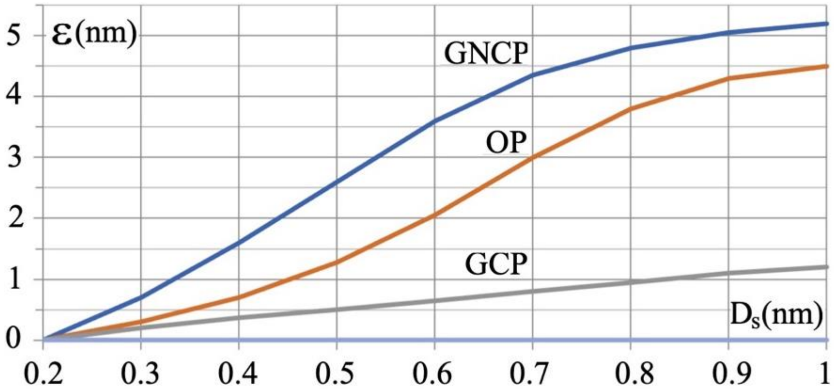


Figure 10: Path deviation ε depending on the safe distance $D_s$ at advance time of manoeuvring $T_a$ = 180 s.

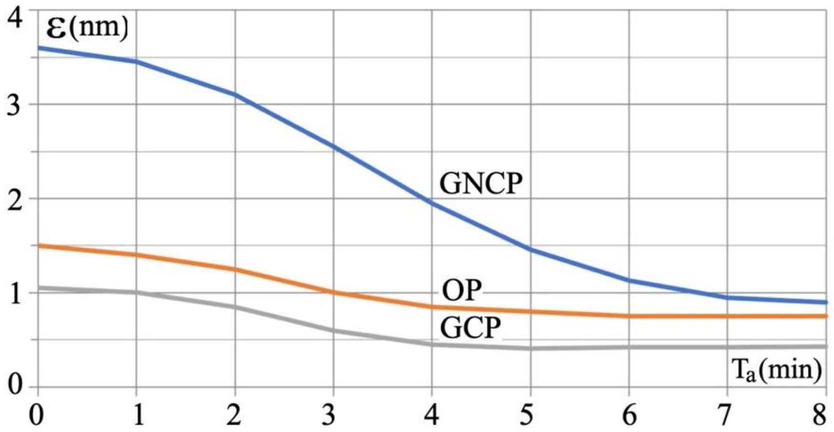


Figure 11: Path deviation ε depending on manoeuvring advance time $T_a$ at safe passing distance $D_s$ = 0.5 nm.

The graphs show that the best results of traffic safety and path optimality are provided by the GCP algorithm, while the GCP algorithm contributes to reducing the collision risk but at the cost of worsening the path optimality. In contrast, the OP algorithm provides a compromise between collision risk and path optimality.

## 5. CONCLUSION

Modelling and simulation of the developed algorithms for determining the safe path in the event of passing many other ships allowed the following final conclusions to be drawn:

- The synthesis of algorithms for determining a safe path for many passing ships using the game model and linear programming optimization made it possible to take into account various real states of the ship traffic environment;
- The introduction of the parameter in the form of manoeuvring advance time made it possible to take into account the ship's dynamic properties;

- The conducted simulation studies allow for the preparation of several versions of algorithms for determining a safe path for practical implementation in the pursuit of a new solution for the ARPA anti-collision system.

Future research should focus on the following:

- The extension of simulation tests for navigational situations representing the movement of several to several dozen ships, both in limited waters and in the open sea;
- Taking into account navigational constraints in fixed algorithms of various shapes;
- The synthesis of an integrated differential game algorithm;
- The assessment of the sensitivity of control quality to the inaccuracy of navigation information and the impact of various environmental disturbances.

## ACKNOWLEDGEMENT

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