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Evolutionary Sets of Safe Ship Trajectories: Evaluation of Individuals

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ABSTRACT: The paper presents a description of the evaluation phase of the Evolutionary Sets of Safe Ship Trajectories method. In general, the Evolutionary Sets of Safe Ship Trajectories method combines some of the assumptions of game theory with evolutionary programming and finds an optimal set of cooperating trajectories of all ships involved in an encounter situation. While developing a new version of this method, the authors decided to use real maps instead of a simplified polygon modelling and also to focus on better handling of COLREGS. The upgrade to the method enforced re-designing the evaluation phase of the evolutionary process. The new evaluation is thoroughly described and it is shown how evaluation affects final solutions returned by the method.

1 INTRODUCTION

A desired solution to a multi-ship encounter situation would include a set of planned, optimal trajectories for all the ships involved in an encounter, such that no collision or domain violations occur when these ships follow the trajectories. When solving this situation the key difficulty is that even a single course change performed by one ship involved in the encounter may force one or even more the other ships to manoeuvre. Thus the optimisation method utilized to find a solution to the problem should be flexible enough to efficiently look through the vast search space and handle even minor changes in the ship's behaviour e.g. in its motion parameters.

There is a number of approaches to solving a multi-ship encounter situation. Two basic trends are either utilization of differential games (Lisowski 2005) or searching for a single trajectory (for the own ship) by evolutionary algorithms (Smierzchalski et al. 2000). The former method assumes that the process of steering a ship in multi-ship encounter situations can be modeled as a differential game played by all ships involved, each having their strategies. Unfortunately, high computational complexity is its serious drawback. The latter approach is the evolutionary method focused on finding only a single trajectory of the own ship. In short, the evolutionary method uses genetic algorithms, which, for a given set of pre-determined input trajectories find a solution that is optimal according to a given fitness function. However, the method's limitation is that it assumes targets motion parameters not to change and if they do change, the own trajectory has to be recomputed. This limitation becomes a serious one on restricted waters. If a target's current course collides with a landmass or another target of a higher priority, there is no reason to assume that the target would keep such a disastrous course until the crash occurs. Consequently, planning the own trajectory for the unchanged course of a target will be futile in the majority of such cases. Also, the evolutionary method does not offer a full support to VTS operators, who might face the task of synchronizing trajectories of multiple ships with many of these ships manoeuvring.

Therefore, the authors have proposed a new approach, which combines some of the advantages of both methods: the low computational time, supporting all domain models and handling stationary obstacles (all typical for evolutionary method), with taking into account the changes of motion parameters (changing strategies of the players involved in a game). Instead of finding the optimal own trajectory (from the own ship's perspective) for the unchanged courses and speeds of targets, an optimal set of safe trajectories of all ships involved is searched for (from the coast, e.g. VTS, perspective). The method is called evolutionary sets of safe trajectories and its early version has been presented by one of the authors in (Szlapczynski 2010).

The newly developed version of the method uses real maps instead of simplified polygon modelling and focuses on COLREGS compliance. The upgrade to the method enforced changes in all phases of the evolutionary process including evaluation. The paper presents a description and a discussion of the new evaluation phase.

The rest of the paper is organized as follows. In the next section a brief description of the problem is given, including basic constraints of the optimization problem as well as the additional constraints - the COLREGS rules, which are taken into account. Section 3 covers the issue of detecting various constraints violations. This is followed by a Section 4, where it is shown, how, on the basis of previous sections, the fitness function is formulated. In section 5 different evaluation approaches and the consequences of applying them are compared by means of simulation experiments. Finally the summary and conclusions are given in Section 6.

2 SOLVING MULTI-SHIP ENCOUNTER SITUATIONS AS AN OPTIMIZATION PROBLEM

It is assumed that we are given the following data:

- stationary constraints (such as landmasses and other obstacles),
- positions, courses and speeds of all ships involved,
- ship domains,
- times necessary for accepting and executing the proposed manoeuvres.

Ship positions and ship motion parameters are provided by ARPA (Automatic Radar Plotting Aid), or, if there is no reliable identification assured, AIS (Automatic Identification System) systems. A ship domain can be determined based on the ship's length, its motion parameters and the type of water region. Since the shape of a domain is dependent on the type of water region, the authors have assumed and used a ship domain model by Davis (Davis et al. 1982), which updated Goodwin model (Goodwin 1975), for open waters and to use a ship domain model by Coldwell (Coldwell 1982), which updated Fuji model (Fuji et al. 1971), for restricted waters.

As for the last parameter – the necessary time, it is computed on the basis of navigational decision time and the ship's manoeuvring abilities. By default an assumed 6-minute value is used here.

Knowing all the abovementioned parameters, the goal is to find a set of trajectories, which minimizes the average way loss spent on manoeuvring, while fulfilling the following conditions:

- none of the stationary constraints are violated,
- none of the ship domains are violated,
- the minimal acceptable course alteration is not lesser than 15 degrees (assumed to eliminate slow and insignificant turns),
- the maximal acceptable course alteration is not to be larger than assumed 60 degrees,
- speed alteration are not to be applied unless necessary (collision cannot be avoided by course alteration up to 60 degrees),
- a ship manoeuvres, if and only if she is obliged to,
- it is assumed that manoeuvres to starboard are favoured over manoeuvres to port board.

The first two conditions are obvious: all obstacles have to be avoided and the ship domain is an area that should not be violated by definition. All the other conditions are either imposed by COLREGS (IMO 1977) and good marine practice or by the economics. In particular, the course alterations lesser than 15 degrees might be misleading for the ARPA systems (and therefore may lead to collisions) and the course alterations larger than 60 degrees are not recommended due to efficiency reasons. Also, ships should only manoeuvre when necessary, since each manoeuvre of a ship makes it harder to track its motion parameters for the other ships ARPA systems (Wawruch 2002). Apart from these main constraints, additional constraints – selected COLREGS rules have to be directly handled.

The COLREGS rules, which are of interest here are:

- Rule 13 – overtaking: an overtaking vessel must keep well clear of the vessel being overtaken.
- Rule 14 - head-on situations: when two power-driven vessels are meeting head-on both must alter course to starboard so that they pass on the port side of the other.
- Rule 15 - crossing situations: when two power-driven vessels are crossing, the vessel, which has the other on the starboard side must give way.
- Rule 16 - the give-way vessel: the give-way vessel must take early and substantial action to keep well clear.
- Rule 17 - the stand-on vessel: the stand-on vessel may take action to avoid collision if it becomes

clear that the give-way vessel is not taking appropriate action.

There are also some additional COLREGS-related assumptions, namely:

- there are always good visibility conditions,
- all considered ships are equally privileged,
- all considered ships have motor engine (no sailing ships taken into account),
- no narrow passages are taken into account
- no port board manoeuvres are assumed when overtaking,
- no manoeuvres to bypass navigational signs are taken into account.

In the following sections it will be analysed how these constraints violations can be detected, in what order should they be taken into account and how severely should they be penalized during the evaluation phase by the fitness function of the evolutionary method.

3 DETECTING CONSTRAINTS VIOLATIONS

Below it is described how the constraints violations can be detected and, in case of various possible approaches, which one has been chosen by the authors and why.

3.1 *Detecting static constraints violations (collisions with landmasses and safety isobate)*

In the first version of the method (Szlapczynski 2009) simplified polygon modelling of the static constraints have been applied, instead of using real maps. Therefore it was natural to find collisions by detecting all crossings of the ships' trajectories with polygons' edges. This is shown in Figure 1. A number of operations that the algorithm has to perform to find collisions in such situation is proportional to the number of the edges of all polygons in a given area.

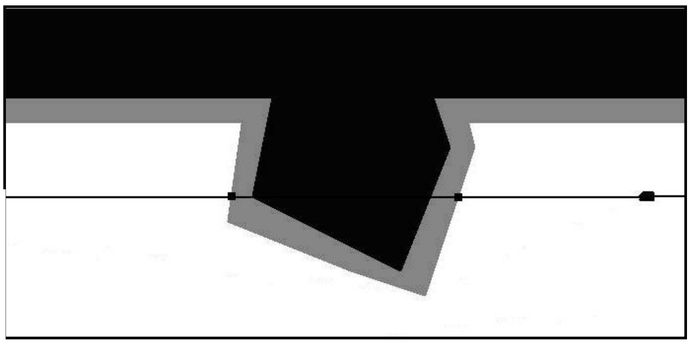

Figure 1. A ship's trajectory crossing a landmass modeled as a polygon. The geometrical crossings of the trajectory and polygon edges are marked in black

However, the current version of the method uses a vector map of a given area. While vector maps also uses polygons defined by coordinates of their vertices, the number of vertices and thus the edges rises drastically, when compared to the simplification used before. Even after limiting the map to a certain area, the numbers of the edges that have to be checked for possible crossings are still much larger. This is shown in Figure 2.

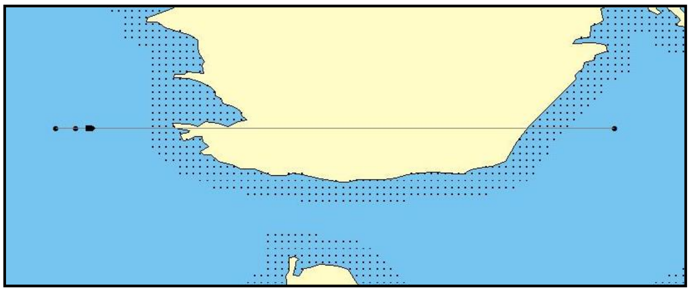

Figure 2. A ship's trajectory crossing a landmass on a bitmap

Therefore the authors have decided not to process vector map directly for crossing detection, but to use it for generating bitmap of an area. Although it is a time-taking operation, fortunately, it is enough to generate such bitmaps offline and only once for each area. Then, when the method is running in real time, instead of checking the edges for geometrical crossings, each bitmap cell, which the trajectory of a ship traverses, is read and checked if it belongs to landmass, water or safety isobate. For a bitmap, whose detail level reflects this of a given vector map, the computational time would be much shorter: proportional to the number of traversed cells, instead of a number of all vertices. This approach is also more flexible in terms of future implementation of bathymetry: if every cell contained information on the water depth, it would be easy to check, whether a cell is passable or not for a particular ship.

3.2 *Detecting collisions with other ships*

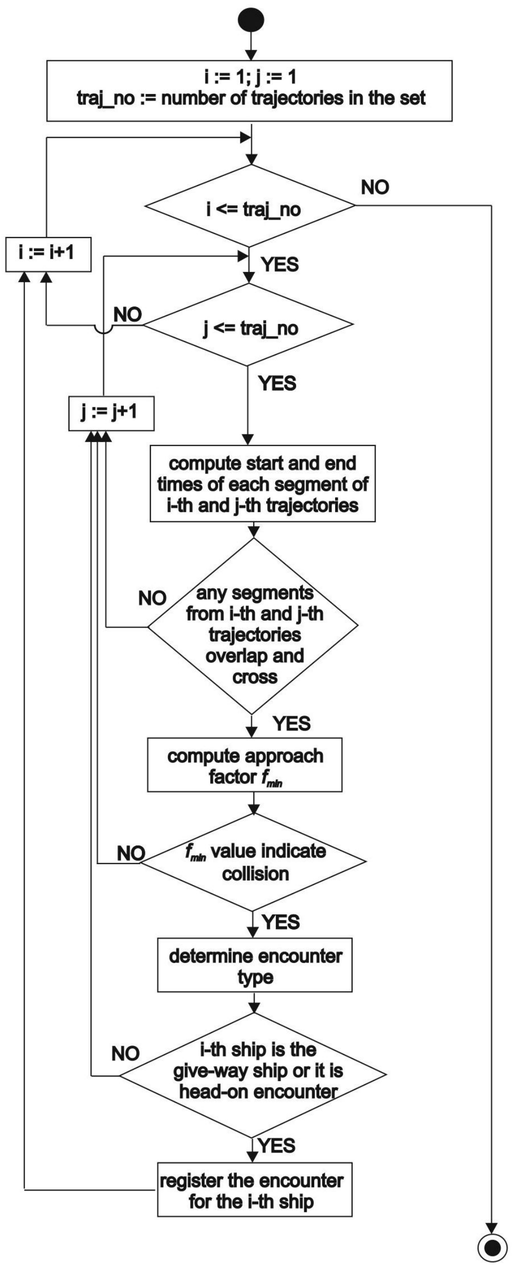

Figure 3. Algorithm for ship-to-ship collision detection

The algorithm for detecting ship-to-ship collisions (Figure 3) is as follows. Each ship's trajectory is checked against all other ships. For each pair of ships, the start time and end time of each trajectory's segments are computed. If two segments of the two trajectories overlap in time, they are checked for geometrical crossing. In case of a crossing, the approach factor value is computed. Then, if the approach factor value indicates collision, the type of an encounter (head-on, crossing or overtaking) is determined on the basis of the ships' courses and it is decided, which ship is to give way (both ships in case of head-on). The collision is only registered for the give way ship and the information on the collision are stored in the trajectory data structure.

3.3 *Detecting COLREGS violations*

Detecting COLREGS violations is much more difficult than violations described in the previous two sub-sections. In general, there may be three types of COLREGS violations:

– a ship does not give way, when it should,
– a ship gives way, when it should not, because it is a stand-on ship,
– a ship manoeuvres to port-board when it should manoeuvre to starboard.

Each of these three situations may happen on either open or restricted waters, which gives us a total of six cases to handle. The difficulty with deciding, whether a ship has acted lawfully, or not, lies in the nature of evolutionary algorithms as well as in the nature of the problem itself: COLREGS specify only the procedures for ship-to-ship encounters. Looking at a set of ship trajectories for a multi-target encounter it is sometimes impossible to tell, what was the reason for a particular manoeuvre: which ship was given way intentionally, and which one benefited from it only as a side effect. A partial solution to this problem is storing in the trajectory data the information on the reasons of the manoeuvres. The possible reasons might be:

– landmass avoidance or other static constraint violation avoidance,
– giving way to a privileged ship,
– any other, e.g. due to the ship's passage plan.

However, the course alterations that each trajectory contains may be made intentionally – as a result of applying a collision avoidance operator or unintentionally – as a result of crossing or mutation. A manoeuvre which resulted accidentally from crossing or mutation may be just as good as the one being the effect of a specialised operator's more 'conscious' work. Therefore the 'any other' manoeuvre's reason cannot always be registered as COLREGS violation. All this considered, the authors have decided to limit the used types on the manoeuvre's reasons to: obstacle avoidance and any other. The final COLREGS violations detection rules are:

1 On open waters:
   a) if a ship is not obliged to give way to any other ship, any manoeuvre (other than the manoeuvres given by the passage plan) it performs is registered as COLREGS violation,
   b) if a ship is obliged to give way, and does not perform a manoeuvre it is registered as COLREGS violation,
   c) all manoeuvres to port board are registered as COLREGS violations.

The c) point may raise some doubts, but it must be emphasized that COLREGS violations registration is done for the sake of future penalizing of violations, when the final fitness function values is being computed. Therefore, the only effect of penalizing the manoeuvres to port board will be additional favouring of manoeuvres to starboard, which are already favoured by domain models. In no way does penalizing make it impossible to choose a manoeuvre to port board. It is only less profitable for most cases.

2 On restricted waters: here, as explained before every trajectory node, which is a part of a manoeuvre, contains special information on the reason why this particular node has been inserted or shifted: land or other stationary obstacle avoidance, target avoidance or accidental manoeuvre generated by evolutionary mechanisms. Based on this, COLREGS violations are registered as follows:
   a) if a ship does not initially have to give way to any target and its first manoeuvre has reason other than static constraint violation avoidance, it is registered as COLREGS violation,
   b) any manoeuvre to port board of reason other than static constraint violation avoidance is registered as COLREGS violation.

   Point b) means that occasionally the correct manoeuvres introduced by crossing or mutation and avoiding static constraint violation will be penalized unjustly. However, it is not a problem, as long as penalties for static constraint violations will be larger and trajectories avoiding them will still be selected for next generations. After all, we are interested in the final sets of trajectories themselves much more than in their slightly imprecise fitness function values.

4 FORMULATING FITNESS FUNCTION

In the evolutionary method all individuals (sets of trajectories) are evaluated by the specially designed fitness function, which should reflect optimisation criteria and constraints (Michalewicz et al. 2004). In this section it is shown, how, on the basis of previous sections, this fitness function is formulated.

4.1 *Basic criterion – minimizing way loss*

The basic criterion is the economic one – minimizing way losses of trajectories in a set. For each of the trajectories, a *trajectory_economy_factor* is computed according to the formula (1).

$$trajectory\_economy\_factor_i = \left(\frac{trajectory\_length_i - way\_loss_i}{trajectory\_length_i} \right), \quad (1)$$

where:

i – the index of the current ship [/],

$trajectory\_length_i$ – the total length of the i-th ship's trajectory [nautical miles],

way_loss_i – the total way loss of the i-th ship's trajectory [nautical miles] computed as a difference between the trajectory length and length of a segment joining trajectory's start point and endpoint.

As can be seen, the *trajectory_economy_factor* is always a number from a (0,1] range.

4.2 *Penalizing static constraint violation*

After the trajectory economy factor has been computed the static constraints are handled by introducing penalties for violating them. For each trajectory its static constraint factor scf_i is computed. The static constraints are always valid and their violations must be avoided at all cost, therefore penalties applied here are the most severe – hence the square in the formula (2).

$$scf_i = \left(\frac{trajectory\_length_i - trajectory\_cross\_length_i}{trajectory\_length_i} \right)^2, \quad (2)$$

where:

$trajectory\_cross\_length_i$ – the total length of the parts of the i-th ship's trajectory, which violate stationary constraints [nautical miles].

The static constraint factor is a number from a [0,1] range, where "1" value means no static constraint violation (no landmasses or other obstacles are crossed) and "0" value is for trajectories crossing landmasses on their whole length.

4.3 *Penalizing collisions with other ships*

Analogically to the static constraint factor, collision avoidance factor caf_i is computed to reflect the ship's collisions with all other privileged ships as shown by (3).

$$caf_i = \prod_{j=1, j \neq i}^{n} \left(\min(fmin_{i,j}, 1) \right) \quad (3)$$

where:

n – the number of ships [/],

j – the index of a target ship [/],

$fmin_{i,j}$ – the approach factor value for an encounter of ships i and j, if i-th ship is the privileged one, the potential collision is ignored and the approach factor value is equal to 1 by definition. [/].

The collision avoidance factor is a number from a [0,1] range, where "1" value means no ship domain violation and "0" means a crash with at least one of the targets.

4.4 *Penalizing COLREGS violations*

The COLREGS violations are secondary to static constraint violations and to collisions with other ships and therefore the authors have decided to penalize it moderately, to make sure that constraints from the previous two points are met first. COLREGS compliance factor ccf_i is computed according to the following formula (4).

$$ccf_i = 1 - \sum_{k=1}^{m} \left[COLREGS\_violation\_penalty_k \right], \quad (4)$$

where:

m – the number of COLREGS violation registered for the current ship as has described in section 3.3 [/],

k – the index of a registered violation [/],

COLREGS_violation_penalty$_k$ – the penalty for the k-th of the registered COLREGS violation [/].

The penalty values for all registered COLREGS violations described in section 3.3 by points 1. a) - c) and 2. a) - b) are configurable in the method and are set to 0.05 by default.

4.5 *Fitness function value*

Once all aforementioned factors have been computed, the fitness function value is calculated. The authors wanted the fitness function to be normalized, which is convenient for further evolutionary operations, mostly for selection purposes. When fitness function values are normalized, we do not need any additional operations on them and they can directly be used for random proportional and modified random proportional selection in the reproduction and succession phases of the evolutionary algorithm. We can also easily measure and see progress we make with each generation. However, normalized fitness function is harder to obtain, because we have to make sure that we keep the high resolution of evaluating the individuals, namely that we differ between various levels of penalties: stationary constraints, being more important than collision avoidance and collision avoidance being more important than COLREGS compliance.

Here, we succeeded in formulating a normalized fitness function, while keeping relatively high resolution of evaluation: minor stationary constraints violations are penalized similarly as major collisions with other ships and minor collisions with other ships are penalized similarly as multiple COLREGS violations. The final fitness function is as follows:

$$fitness = \sum_{i=1}^{n} \frac{trajectory\_fitness_i}{n}, \quad (5)$$

where:

$$trajectory\_fitness_i = \\ = trajectory\_economy\_factor_i * scf_i * caf_i * ccf_i, \quad (6)$$

The final fitness function value assigned to an individual is an arithmetical average of fitness function values computed for all trajectories. It is discussable, whether all trajectories should have the same impact on final fitness function value (as it is done here), or should the trajectory fitness function values be taken with weights proportional to the trajectory lengths. When combined with the formula for trajectory economy factor, the current approach means that we are trying to minimize average relative way loss computed over all trajectories, instead of total absolute way loss (with weights being used). However, experiments have shown, that minimizing total absolute way loss leads to discrimination of ships, whose basic trajectories are shorter and to their large relative way losses (section 5.2).

5 COMPARING DIFFERENT EVALUATION APPROACHES

In the following subsections different evaluation approaches and the consequences of applying them are compared.

5.1 *Penalizing COLREGS violations: how it affects solutions returned by the method*

Even when a domain model, which favours COLREGS is applied, it is possible to find an encounter situation, where additional COLREGS violations penalties must be used, as has been described in section 4.4 or otherwise the method will return incorrect solution. A simple example is a head-on encounter of two ships, whose parameters are shown in Figure 4. In this scenario, following the Rule 14 of COLREGS for head-on situations, it is required that:

"(...) both (vessels) must alter course to starboard so that they pass on the port side of the other".

Ship Parameters

	Initial pos	Goal pos	Velocity [kn]	Turn [deg./sec.]
Ship1	(7.03 ; -10.56)	(-1.37 ; 12.91)	12.47	1.00
Ship2	(-2.67 ; 13.58)	(8.22 ; -11.29)	13.57	1.00

Figure 4. Parameters of two ships in a head-on encounter

Because the method tends to propose manoeuvres no lesser than 15 degrees, a manoeuvre from one ship only would be enough to avoid collision. From the way loss minimization point of view, the extra manoeuvre from the second ship is redundant. Consequently, individuals containing trajectories with manoeuvres from both ships would be ranked lower than those with only one ship manoeuvring and the final solution will have only one ship manoeuvring, which is shown in Figure 5.

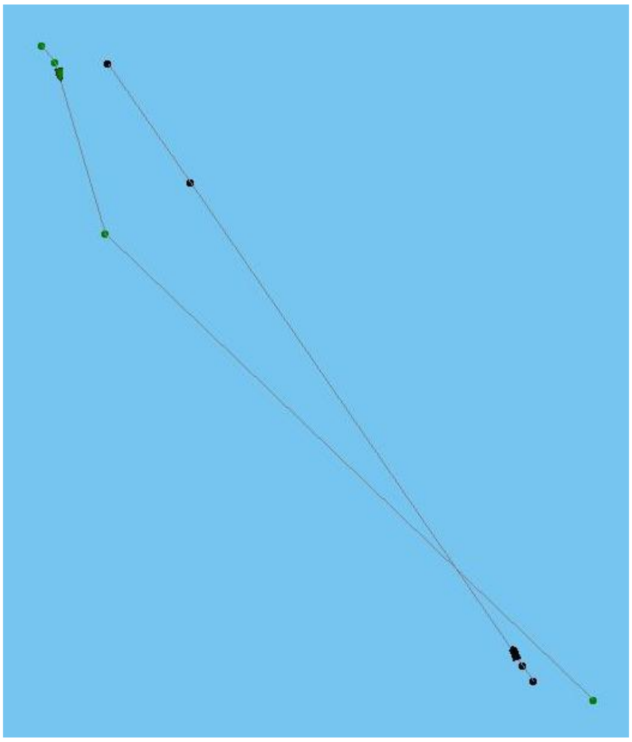

Figure 5. An incorrect solution to a head-on encounter situation returned by the method without COLREGS violations penalties

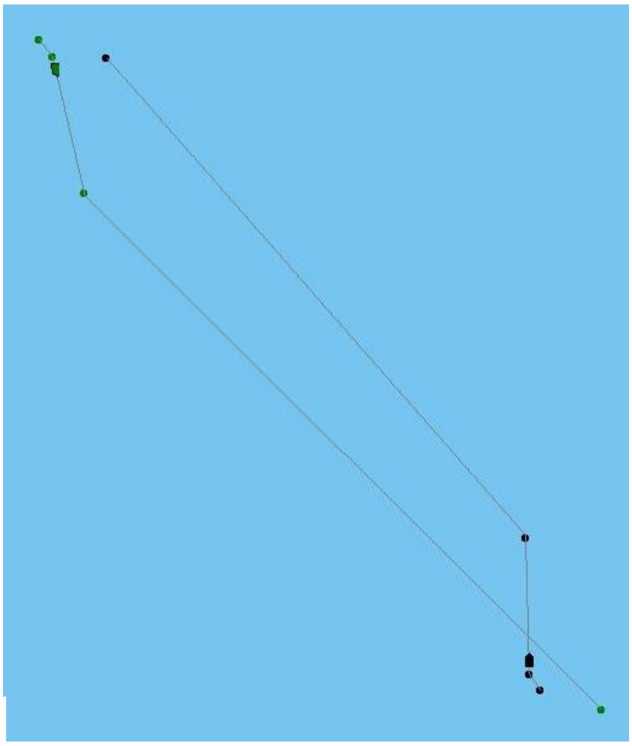

Figure 6. A correct solution to a head-on encounter situation returned by the method with COLREGS violations penalties applied

Thus we need to additionally penalize the individuals for COLREGS violations to favour the individuals with both ships manoeuvring and larger way loss. The default penalties of 0.05 are sufficient for the correct solution to be chosen. This is shown in Figure 6.

5.2 *Optimization criterion: total absolute way loss or average relative way loss*

Another question already raised before (section 4.5) is whether we should minimize total absolute way loss or average relative way loss. An example scenario of an encounter of 6 ships on restricted waters is presented below. Ship parameters are gathered in Figure 7. The results of minimizing total absolute way loss are shown in Figure 8, the results for the minimization of average relative way loss – in Figure 9.

Zero longitude 20.5 Zero latitude 58.5

Ship Parameters

	Initial pos	Goal pos	Velocity [kn]	Turn [deg./sec.]
Ship1	(58.28 ; 163.55)	(67.26 ; 138.75)	13.19	1.00
Ship2	(54.19 ; 139.40)	(71.34 ; 162.89)	14.54	1.00
Ship3	(79.25 ; 157.53)	(46.29 ; 144.76)	17.67	1.00
Ship4	(73.59 ; 145.04)	(51.93 ; 157.24)	12.43	1.00
Ship5	(70.05 ; 138.46)	(55.65 ; 163.90)	14.61	1.00
Ship6	(48.01 ; 144.18)	(71.99 ; 155.82)	13.32	1.00

Figure 7. Parameters of six ships in an encounter on restricted waters

As can be seen below, minimizing average relative way loss (Figure 9) results in smoother trajectories for ship 1 and ship 5. Ship 5 also has considerably lesser way loss because it passes the island on its left side (Figure 9), instead of right side (Figure 8). Other trajectories (the longer ones) have no major visual differences between them in Figures 8 and 9, though fitness function values of some ships are slightly larger for Figure 8, because of their (insignificantly) lesser way losses. Unfortunately, it is impossible to formally compare the solutions returned by the two variants of the method, which use different formulas for global fitness function and thus aim at different goals. However, after a series of simulation experiments, the authors are of the opinion that in general the minimization of average relative way loss brings more balanced and intuitive results for most cases and therefore have chosen it to be the default option of the current version of the Evolutionary Sets of Safe Trajectories method.

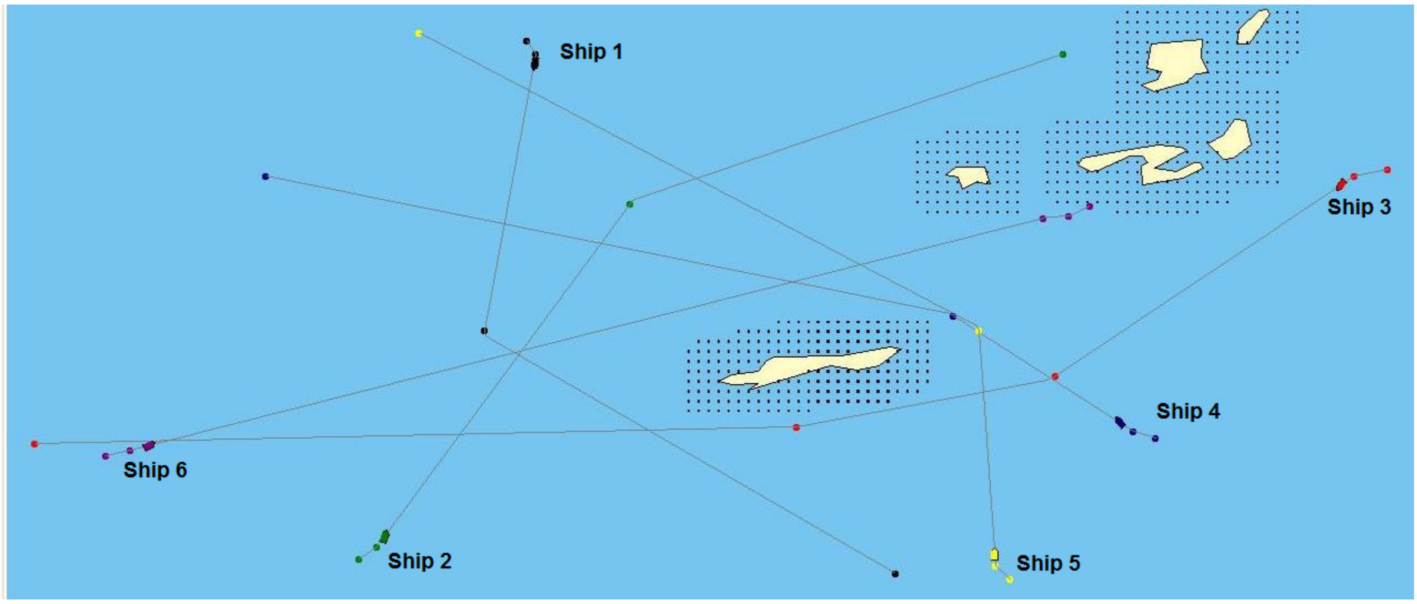

Figure 8. A solution to a multi-ship encounter situation returned by the method with minimization of total absolute way loss

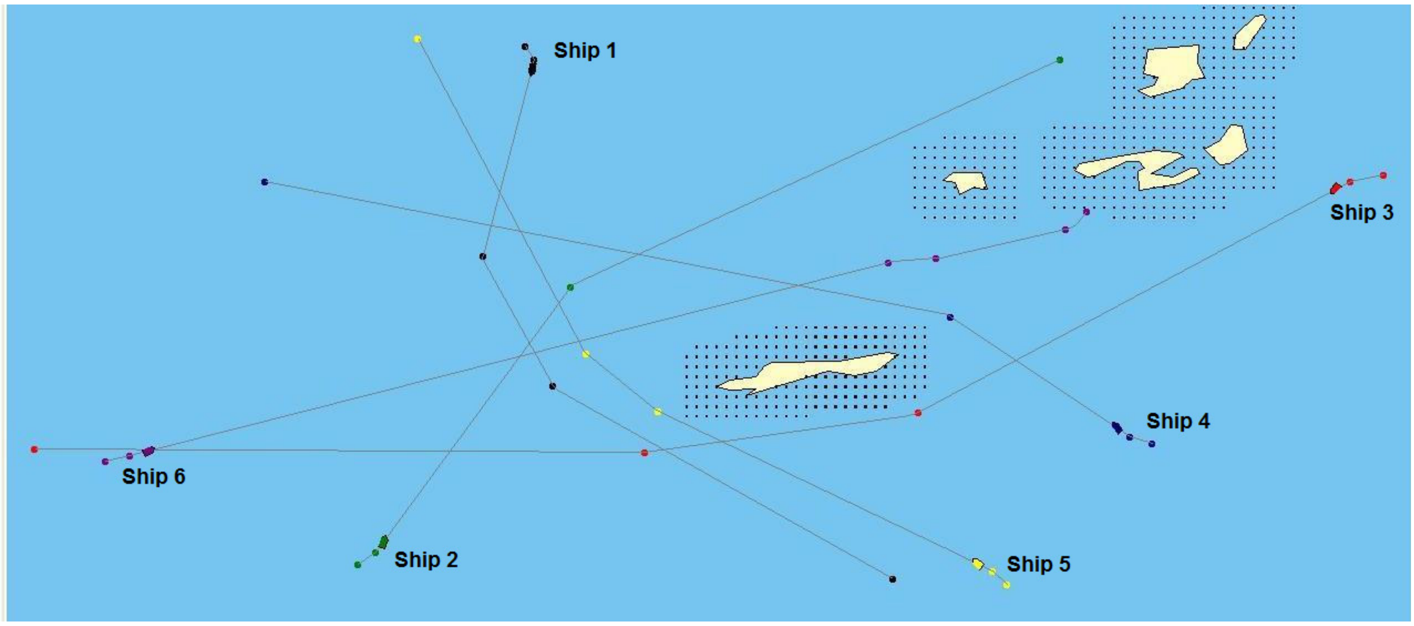

Figure 9. A solution to a multi-ship encounter situation returned by the method with minimization of average relative way loss

6 SUMMARY AND CONCLUSIONS

The paper documents the research on the evaluation phase of the Evolutionary Sets of Safe Ship Trajectories method. For some of the optimisation constraints, gathering the data on their violations for evaluation purposes is time consuming (collisions with other ships and static obstacles), while for others it is discussable in some cases, whether a constraint has been met or not (COLREGS rules), which seriously limits detection possibilities. Even such a seemingly simple issue as main optimisation criterion (way loss minimisation) becomes a problem, when a particular fitness function value is to be formulated. The authors have explored various possibilities of gathering the data on constrain violation, as well as using them in the fitness functions and have presented in the paper their conclusions: the techniques and formulas that, in the course of the research, occurred to be most useful for evaluation of the sets of ship trajectories.

The chosen elements of the method have been illustrated by simulation examples showing how a change in the evaluation phase affects the final solutions returned by the method. The authors' search for the optimal evaluation is being continued, as the whole method's functional scope is expanding. The current works are focused on handling Traffic Separation Schemes directly in the Evolutionary Sets of Safe Trajectories method, which brings new evaluation issues.

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