COLREGS COMPLIANCE IN EVOLUTIONARY SETS OF COOPERATING SHIP TRAJECTORIES

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ABSTRACT

In general, Evolutionary Sets of Cooperating Ship Trajectories combine some of the assumptions of game theory with evolutionary programming and aim to find optimal set of cooperating trajectories of all ships involved in an encounter situation. In a two-ship encounter situation the method enables the operator of an on-board collision-avoidance system to predict the most probable behaviour of a target and to plan the own manoeuvres in advance. In a multi-ship encounter the method may be used to help an operator of a VTS system to coordinate the manoeuvres of all ships. The improvement presented here is a new way of modelling some of the COLREGS rules. Due to this change, the method is now able to find solutions, which are more compliant with COLREGS, more intuitive and consequently – safer from the navigator's point of view. The paper contains a detailed description of collision-avoidance operators used by the evolutionary method and simulation examples of the method's results for digital maps.

1. INTRODUCTION

The main approaches to the problem of planning optimal ship trajectories in encounter situations are based on either differential games or on evolutionary programming. The former method has been introduced by Lisowski (2005) and it assumes that the process of steering a ship in multi-ship encounter situations can be modelled 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 of finding the trajectory of the own ship, proposed by Smierzchalski & Michalewicz (2000). Especially the second approach is recently very popular among researchers – it may be applied for finding an optimal path (Zeng, 2003) as well as an optimal collision avoidance manoeuvre (Tsou et al., 2010). 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.

Therefore, the authors have decided to try 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 for the unchanged courses and speeds of targets, an optimal set of safe trajectories of all ships involved is searched for. The method is called evolutionary sets of safe trajectories and one of its earlier versions has been presented in (Szlapczynski, 2009).

One of the important issues of the method is applying to the International Regulations for Preventing Collisions at Sea (Cockroft & Lameijer 1993). The COLREGS rules, which are discussed 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.

The main idea of the improvement, presented here is that COLREGS are modelled directly in the fitness function, instead of reflecting them indirectly on many other levels of the method. The rest of the paper is organized as follows. Section 2 describes the foundations of the collision avoidance method based on evolutionary sets of cooperating trajectories. Section 3 focuses on the details of the new approach to COLREGS, followed by same example results, which are shown in section 4. Finally, summary and conclusions are given in section 5.

2. EVOLUTIONARY SETS OF COOPERATING SHIP TRAJECTORIES

Evolutionary Sets of Cooperating Ship Trajectories (Szlapczynski 2009) is a name of a method solving multi-ship encounters. Foundations of the method are presented in the following subsections. The description includes definition of the optimization problem and some aspects of evolutionary engineering applied to the problem.

2.1. Optimisation problem

It is assumed that we are given the following data:

- stationary constraints (obstacles and other constraints modelled as polygons),
- 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) 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 dependant on the type of water region, the author has decided to use a ship domain model by Davis (Davis et al. 1982) for open waters and to use a ship domain model by Coldwell (1982) 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 a 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,
- the maximal acceptable course alteration is not be larger than 60 degrees,

- speed alteration are not to be applied unless necessary (collision cannot be avoided by course alteration up to 60 degrees),
- a ship only manoeuvres, when it is obliged to,
- manoeuvres to starboard are favoured over manoeuvres to port board.

2.2. Evolutionary issues

The general idea of evolutionary programming is shown in Figure 1.

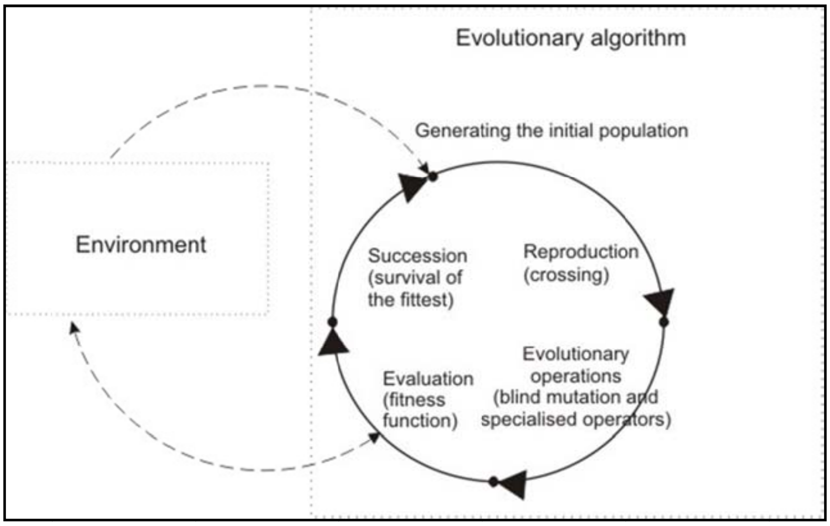

Figure 1. Evolutionary algorithm

First, the initial population of individuals (each being a potential solution to the problem) is generated either randomly or by other methods. Usually none of these individuals is optimal or even close to that. Sometimes none of the individuals is acceptable. This initial population is a subject to subsequent iterations of evolutionary algorithm. Each of these iterations consists of the following steps:

1. Reproduction: sets of parents (usually pairs) are selected from all of the individuals and they are crossed to produce offspring. The offspring inherits some features from each parent.
2. Evolutionary operations: the offspring is modified by means of random mutation operators as well as specialized operators dedicated to the problem.
3. Evaluation: each of the individuals (including parents and the offspring) is assigned a value of a fitness function, which reflects the quality of the solution represented by this individual.
4. Succession: the next generation of individuals is selected. The selection is based on the results of the evaluation. Usually the individuals are chosen randomly, with the probability strictly depending on the fitness function value.

The evolutionary algorithm ends when one of the following happens:

- maximum acceptable time or number of iterations is reached,
- the satisfactorily high value of fitness function has been reached by one of the individuals,
- further evolution brings no improvement.

3. COLREGS COMPLIANCE

3.1. Basic fitness function

The following basic fitness function is used to assess the quality of a solution:

$$fitness = \sum_{i=1}^{n} [tr\_fit_i], \tag{1}$$

where:

$$tr\_fit_i = \left(\frac{tr\_length_i - way\_loss_i}{tr\_length_i} \right) * sf_i * of_i, \tag{2}$$

sf_i - ship collision factor [/] of the *i*-th ship computed over all prioritised targets:

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

of_i - obstacle collision factor [/] of the *i*-th ship computed over all stationary constraints:

$$of_i = \left(\frac{trajectory\_length_i - trajectory\_cross\_length_i}{trajectory\_length_i} \right)^2 \tag{4}$$

n – the number of ships [/],
m – the number of stationary constraints [/],
i – the index of the current ship [/],
j – the index of a target ship [/],
k – the index of a stationary constraint [/],
$fmin_{i,j}$ – the approach factor value for an encounter of ships *i* and *j* [/],
$trajectory\_length_i$ – the total length of the i-th ship's trajectory [nautical miles]
$trajectory\_cross\_length_i$ – the total length of the parts of the i-th ship's trajectory, which violate stationary constraints [nautical miles]

This fitness function focuses on way loss and safe distances between ships, with COLREGS only being applied via ship domain models used to compute the approach factor value (Szlapczynski 2006b). The impact of ship domain model on COLREGS compliance is as follows. Domain shape affects the size of necessary course alteration manoeuvres to starboard and port board, thus affecting way loss and indirectly – fitness function values assigned to different trajectories. Therefore applying asymmetrical ship domain, whose port board area is larger than starboard area, favours manoeuvres to starboard over manoeuvres to port board. Also, larger bow area makes it less likely to cross ahead of stand-on targets. Apart from ship domains, two other means of reaching compliance with COLREGS have been applied:

1. Only collisions with prioritised ships were taken into account so as not to encourage unnecessary or unlawful manoeuvres from so-called "stand-on" vessels.
2. Manoeuvres to starboard were encouraged by a larger probability of course alteration to starboard than port board in mutation and specialised operators:
   - node shift,
   - node insert,

- segment shift
- segment insert in and mutation.

3.2 Penalties for breaking COLREGS

Once the basic fitness function has been computed according to the formulas from Section 3.1, the penalties are applied according to the following rules:

1. On open waters:
   a. if a ship is not obliged to give way, any manoeuvre it performs is penalized,
   b. if a ship is obliged to give way, and does not perform a manoeuvre it is penalized,
   c. all manoeuvres to port board are penalized.

2. On restricted waters: 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 penalties are applied as follows:
   a. if a ship does not initially have to give way to any target and its first manoeuvre has reason other than stationary obstacle avoidance, it is penalized,
   b. any manoeuvre to port board of reason other than stationary obstacle avoidance is penalized.

For normalized initial fitness function values, the penalties resulting from the unlawful manoeuvres have been set to 0.05. The penalties are additive that is a manoeuvre might be penalized twice. For example a manoeuvre to port board form a stand-on ship would be first penalized for performing any manoeuvre at all (rule 1a) and then, additionally for altering its course to port board (rule 1c).

4. RESULTS OF THE NEW APPROACH: SCENARIOS AND EXAMPLES

This section presents simulation results returned by a software application designed by the authors. The application implements evolutionary sets of cooperating ship trajectories including the abovementioned COLREGS compliance mechanisms. Following subsections present encounter examples on open and restricted waters for various ships configurations.

4.1 Open water basic scenario #*1*

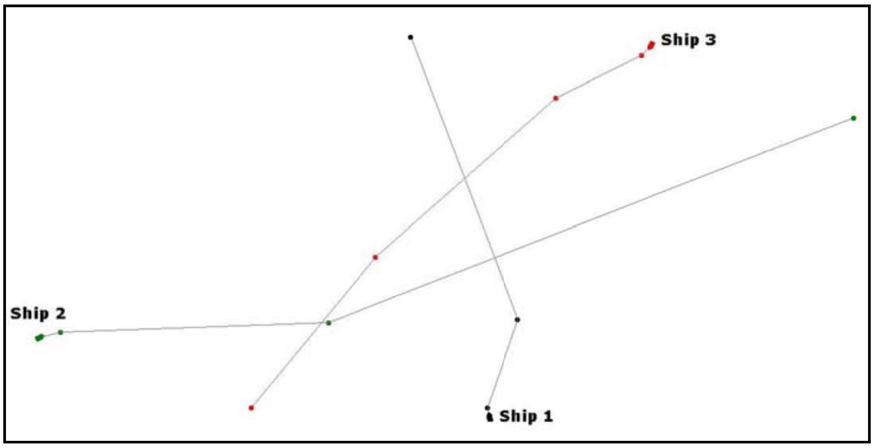

Figure 2. Open water basic scenario #1 – simulation starting screenshot

Table 1. Open water basic scenario #1 – ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	20° 34’ 10” E 58° 24’ 29” N	20° 31’ 37” E 58° 36’ 46” E	11.46	0.9595	0.9796
Ship 2	20° 19’ 34” E 58° 27’ 02” N	20° 45’ 58” E 58° 34’ 09” N	14.42	0.9842	
Ship 3	20° 39’ 26” E 58° 36’ 29” N	20° 26’ 27” E 58° 24’ 47” N	12.55	0.9726	

In the scenario presented in Figure 2 all three ships have similar situation of having one ship starboard and one port-board. Thus all these ships have to manoeuvre as follows: ship 1 gives way to ship 3, ship 3 gives way to ship 2 and ship 2 gives way to ship 1. The resulting trajectories assure that all the ships manoeuvre safely and there are no ahead crossings. Due to the specific positions and speeds (Table 1) ship 1 has the largest (the smallest fitness value) and ship 2 the smallest way loss (the largest fitness value).

4.2 Open water basic scenario *#2*

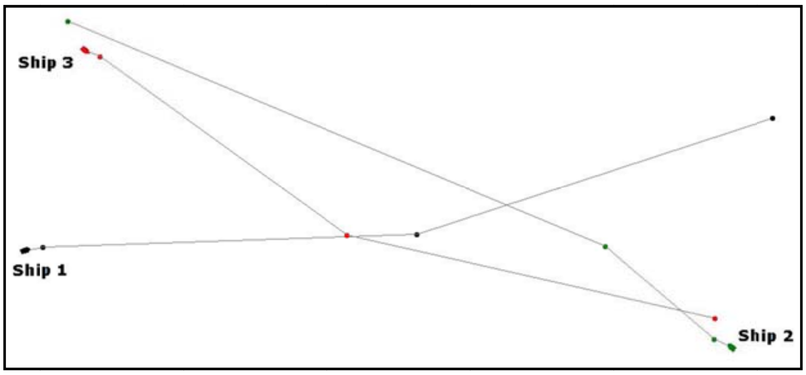

Figure 3. Open water basic scenario #2 – simulation starting screenshot

Table 2. Open water basic scenario #2 – ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	20° 20’ 45” E 58° 28’ 28” N	20° 44’ 57” E 58° 32’ 45” N	12.41	0.9806	0.9821
Ship 2	20° 43’ 35” E 58° 25’ 21” N	20° 22’ 08” E 58° 35’ 53” N	14.28	0.9856	
Ship 3	20° 22’ 41” E 58° 34’ 58” N	20° 43’ 05” E 58° 26’ 17” N	12.77	0.9591	

In the scenario presented in Figure 3 ship 2 & ship 3 have a head-on encounter while crossing with ship 1. Thus, ship 2 & ship 3 should alter their courses to starboard. Additionally ship 3 should give way to ship 1, while ship 1 should give way to ship 2. The resulting trajectories assure that all the restrictions are met and again there is no ahead crossing. In this situation (Table 2) ship 3 has to take a roundabout way resulting in the largest way loss (smallest fitness value).

4.3 Open water complex scenario

In the scenario presented in Figure 4 (with ship positions given in Table 3) there is a single ship (ship 1) crossing with two group of ships, namely:

- first group formed by ship 2, ship 3 and ship 4,
- second group formed by ship 5 and ship 6.

Ship 1 is a give-way vessel only to the first group of ships, thus it performs a substantial starboard course alteration to avoid ahead crossing. Ships 2, 3 & 4 are stand-on vessels (having no other vessels to their starboard) and due to that their courses remain unchanged until reaching their destination positions (maximum possible trajectory fitness value of 1.0). Unlike group 1, ships 5 & 6 from group 2 must give way to both ship 1 and group 1 ships. Due to mutual relation between origin and destination positions of ship 5 and ship 6 the former alters her course to port board, while the latter – to starboard. This way ship 5 reaches her destination safely bypassing ships 1, 2, 3 & 4 ahead with substantial distance to the ships. On the other hand, ship 6 avoids ahead crossing by her starboard maneuver. If both ship 5 & ship 6 changed courses to starboard, ship 6 would be forced to perform a larger alteration and the resulting way loss of the ships would be greater.

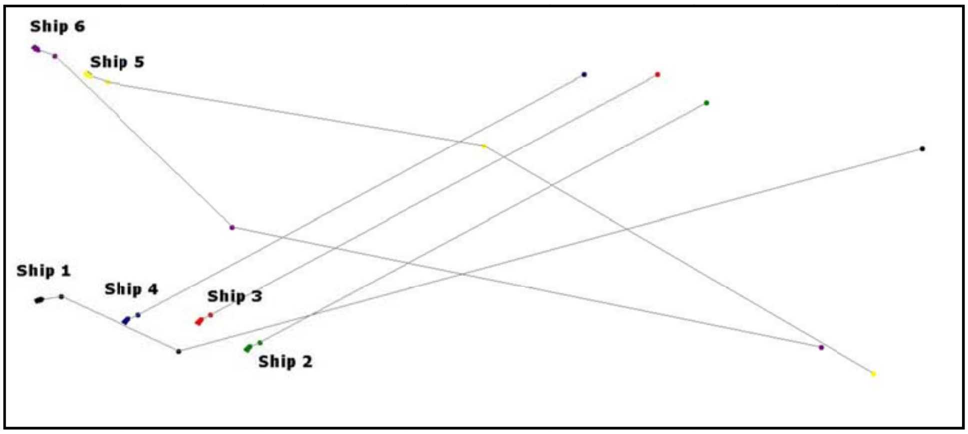

Figure 4. Open water complex scenario – simulation starting screenshot

Table 3. Open water complex scenario – ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	20° 18’ 29” E 58° 28’ 08” N	20° 47’ 17” E 58° 33’ 06” N	14.73	0.9275	0.9872
Ship 2	20° 25’ 17” E 58° 26’ 34” N	20° 40’ 14” E 58° 34’ 37” N	10.41	1.0000	
Ship 3	20° 23’ 42” E 58° 27’ 27” N	20° 38’ 39” E 58° 35’ 30” N	10.41	1.0000	
Ship 4	20° 21’ 20” E 58° 27’ 28” N	20° 36’ 16” E 58° 35’ 31” N	10.41	1.0000	
Ship 5	20° 20’ 04” E 58° 35’ 30” N	20° 45’ 41” E 58° 25’ 44” N	15.39	0.9575	
Ship 6	20° 18’ 21” E 58° 36’ 21” N	20° 43’ 59” E 58° 26’ 36” N	15.39	0.8984	

4.4 Restricted water basic scenario #*1*

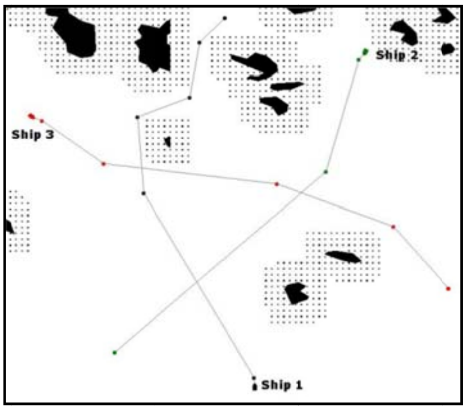

Figure 5. Restricted water basic scenario #1 – simulation starting screenshot (dotted areas depict non-approachable regions)

Table 4. Restricted water basic scenario #1– ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	21° 03’ 33” E 60° 04’ 35” N	21° 02’ 18” E 60° 20’ 05” N	14.39	0.9345	0.9481
Ship 2	21° 08’ 11” E 60° 18’ 39” N	20° 57’ 40” E 60° 06’ 02” N	12.78	0.9855	
Ship 3	20° 54’ 10” E 60° 15’ 57” N	21° 11’ 41” E 60° 08’ 44” N	10.82	0.9547	

In the scenario presented in Figure 5 (with ship positions given in Table 4) all the ships have one ship starboard and one port board, similar to open water scenario #1, but here ships also have to bypass obstacles (landmasses and areas limited by safety isobate). Ship 1 initially maneuvers to port board, securing safe bypassing of ship 2, ship 3 and obstacle being on her way. Later ship 1 has to change her course three more times to reach her destination hidden behind islands. Ship 2, although having ship 3 on her starboard requires only a small course alteration to port board to safely bypass the other ships. Possible collision threat between ship 2 and ship 3 is diminished also by initial starboard course change of ship 3, made originally due to obstacle bypassing.

4.5 Restricted water basic scenario #*2*

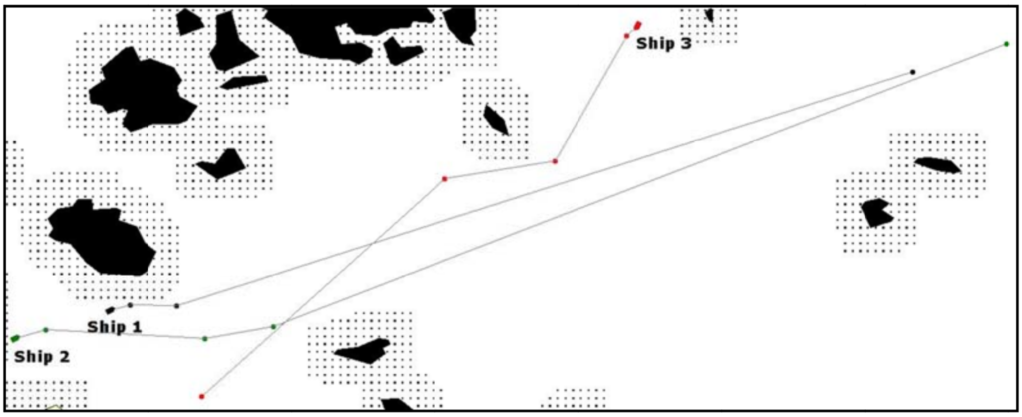

Figure 6. Restricted water basic scenario #2 – simulation starting screenshot (dotted areas depict non-approachable regions)

Table 5. Restricted water basic scenario #2 – ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	20° 40’ 34” E 60° 05’ 21” N	21° 06’ 28” E 60° 13’ 03” N	14.46	0.9930	0.9716
Ship 2	20° 37’ 32” E 60° 04’ 27” N	21° 09’ 30” E 60° 13’ 57” N	22.05	0.9735	
Ship 3	20° 57’ 36” E 60° 14’ 32” N	20° 43’ 33” E 60° 02’ 36” N	13.00	0.9587	

In the scenario presented in Figure 6 (with ship positions given in Table 5) a group of two ships (ship 1 & ship 2) crosses with ship 3, while in the group ship 1 is overtaken by ship 2. Ship 1 as the stand-on vessel in this case has to perform only a slight starboard alteration to avoid an obstacle and then keeps her course. Ship 2 as the overtaking vessel performs a substantial starboard alteration to safely bypass ship 1. Ship 3 must initially change her course to port board to avoid collision with an obstacle and then gets back to course towards her destination points, having ship 1 and ship 2 safely bypassed astern.

4.6 Restricted water complex scenario

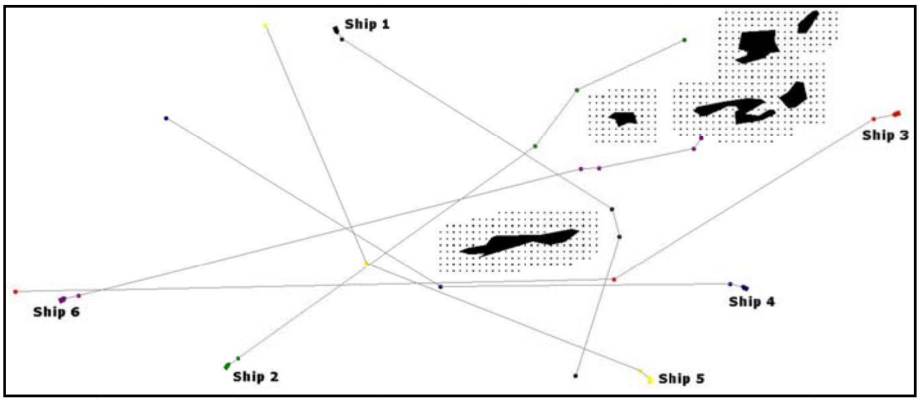

Figure 7. Restricted water complex scenario – simulation starting screenshot (dotted areas depict non-approachable regions)

Table 6.Restricted water complex scenario – ship positions & resulting fitness values

	Origin position	Destination position	V [kn]	Resulting trajectory fitness value [/]	Resulting general fitness value [/]
Ship 1	21° 29’ 58” E 59° 58’ 05” N	21° 39’ 13” E 59° 44’ 44” N	13.18	0.9137	0.9565
Ship 2	21° 25’ 45” E 59° 45’ 05” N	21° 43’ 24” E 59° 57’ 44” N	14.54	0.9909	
Ship 3	21° 51’ 33” E 59° 54’ 51” N	21° 17’ 38” E 59° 47’ 58” N	17.67	0.9139	
Ship 4	21° 45’ 43” E 59° 48’ 07” N	21° 23’ 26” E 59° 54’ 42” N	12.43	0.9004	
Ship 5	21° 42’ 05” E 59° 44’ 35” N	21° 27’ 15” E 59° 58’ 17” N	14.61	0.9374	
Ship 6	21° 19’ 24” E 59° 47’ 39” N	21° 44’ 04” E 59° 53’ 56” N	13.32	0.9893	

To facilitate analysis of a scenario presented in Figure 7 (with ship positions given in Table 6) let's divide the ships as follows:

1. ship 3, ship 4 & ship 5, forming group 1, heading westbound,
2. ship 2 and ship 6, forming group 2, heading eastbound,
3. ship 1 heading southbound.

All group 1 ships must bypass an obstacle and perform this action by port board maneuvers assuring safe astern crossings. In the group 2 alone there a slight crossing threat and ship 2 & ship 6 are forced to minor course amendments. However, still group 2 ships have impact on ship 1 and ship 5 maneuverings. Ship 1 is in the worst situation here: she has to bypass a large obstacle (the same as group 1 & 2 but larger north-southbound than west-eastbound), give way to group 2 ships and make sure her maneuvering won't disturb group 1. Successfully ship 1 makes her so by severe port board course change and astern bypassing trajectories of ship 3, ship 4 and ship 5.

5. SUMMARY AND CONCLUSIONS

The paper presents a newly designed and implemented improvement to the evolutionary sets of safe trajectories method. The method finds the optimal or near optimal set of safe ship trajectories for given positions and motion parameters of all ships involved in an encounter situation. The method is a generalization of evolutionary trajectory determining.

A set of trajectories of all ships involved, instead of just the own trajectory, is determined. The method avoids violating ship domains and stationary constraints, while obeying the COLREGS and minimizing total way loss computed over all trajectories. Because of its low computational time the method can be applied to on-board collision-avoidance systems and VTS systems. In the former, in case of simple scenarios (where ship priorities are clearly described by COLREGS), the method is able to predict the most probable manoeuvre of a target and plan own ship manoeuvre in advance, so that own manoeuvre could be initiated as soon as the target's manoeuvre is executed. In the latter, due to central planning, it could successfully solve any given scenario involving multiple ships and stationary constraints. The improvement, which the paper focuses on, is a set of rules that update fitness function values by penalizing unlawful manoeuvres. The solution has been tested and its better compliance with COLREGS has been confirmed by the experiments, whose examples are given in section 4.

The current version of the method is therefore able to plan trajectories not only of minor way loss spent on collision avoidance manoeuvres but also of full compliance with regulations and therefore – much safer. The further research on the method is planned and it will focus on VTS-specific issues and on planning ship trajectories on Traffic Separation Schemes with high ship density.

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