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Evolutionary sets of cooperating ship trajectories: COLREGS compliance

Keywords

evolutionary algorithms, multi-ship encounters, anti-collision, COLREGS

Abstract

The paper presents a newly designed improvement to the method of solving multi-ship encounter situations. In general, the method combines some of the assumptions of game theory with evolutionary programming and aims to find optimal set of cooperating trajectories of all ships involved in an encounter situation. 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.

1. Introduction

The paper contains a description of an already developed, revised version of the method, which has been first presented by one of the authors in its early version in [6]. In general, the method combines some of the assumptions of game theory applied to the problem of planning safe ship trajectories [4] with evolutionary programming [7] and aims to find an optimal set of cooperating trajectories of all ships involved in an encounter situation, by means of evolutionary algorithms. One of the important issues of the method is applying to the International Regulations for Preventing Collisions at Sea (COLREGS) [1]. 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. Earlier approach to modelling COLREGS with both its advantages and disadvantages is presented in section 3. On contrary, section 4 focuses on the details of the new approach, followed by same example results, which are shown in section 5. Finally, summary and conclusions are given in section 6.

2. Evolutionary sets of cooperating ship trajectories

Evolutionary Sets of Cooperating Ship Trajectories [6] 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 [3] for open waters and to use a ship domain model by Coldwell [2] 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 evolutionary process works as follows. First, the initial population of individuals (each being a potential solution to the problem) is generated either randomly or by other methods.
Each member of the population (called an individual) is a set of trajectories, each trajectory corresponding to one of the ships involved in an encounter. A trajectory is a sequence of nodes, each node containing the following data:

- geographical coordinates x and y,
- the speed between the current and the next node.

Usually none of the individuals from the initial population is optimal or even close to that. Sometimes none of them is acceptable. The initial population is a subject to subsequent iterations of evolutionary algorithm. Each of these iterations consists of the following steps:
1) Reproduction: pairs of individuals are selected from all of the population members 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 and the selection is strictly based on the results of the evaluation.

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. Earlier approach to the problem of modelling COLREGS

Previous approach to handling COLREGS in the method as well as its consequence is presented in the following subsections. The description includes key formulas and comments on correctness of the approach.

3.1. The approach

The following fitness function has been used in the previous version of the method:

$$fitness = \sum_{i=1}^{n} \left[tr\_fit_i \right], \quad (1)$$

where:

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

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

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

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

$$of_i = \prod_{k=1}^{m} \left(\frac{360° - collision\_course\_range_j}{360°} \right) \quad (4)$$

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 [/],
$collision\_course\_range_j$ - the range of forbidden courses of the ship i computed for the stationary constraint j in the node directly preceding the collision. [/].

This fitness function focused on way loss and safe distances between ships, with COLREGS only being applied via ship domain models [2, 3] used to compute the approach factor value [5]. 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:

- Only collisions with prioritised ships were taken into account so as not to encourage unnecessary or unlawful manoeuvres from so-called “stand-on” vessels.
- 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. How well it worked

In majority of the cases the approach turned out to be successful. However occasionally the method would still choose manoeuvre not recommended by COLREGS due to minimizing way loss. The manoeuvres not recommended by COLREGS occurred most often for the situations of:

- head-on encounters of two ships, when one of the ships would perform a course alteration large enough to avoid collision and the second ship would keep its course despite the fact, that it should perform a manoeuvre as well,
- crossing encounters, when choosing a manoeuvre to port board results in a lesser way loss, despite choosing a domain model, which favours manoeuvres to starboard,
- crossing encounters, when manoeuvre from a stand-on vessel would result in a lesser global way loss than a manoeuvre form give-way ship.

In general, all of these undesired cases would occur, when evolutionary process would accidentally generate a very unlikely solution, which can be assigned high fitness function value (due to low way loss) despite unlawful manoeuvres.

4. New approach – applying COLREGS directly in fitness function

This time a different fitness function has been designed. It includes penalties for collision avoidance actions not recommended by COLREGS. The rules of applying these penalties are different for restricted and open waters due to the fact that on restricted waters manoeuvres may result from avoiding collisions with land and other stationary obstacles as well as with targets. In general, the fitness function is first computed according to the formulas from Section 3.1 and then 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).

5. 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.

5.1. Head-on situation involving two ships on open waters

Example data of a two-ship head-on encounter on open waters is presented in *Table 1.* Simulation result is presented in *Figure 1.* Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=18.0° E and y_0=56.0° N.

In this scenario both ships performed starboard manoeuvres, which are default and COLREGS compliant behaviour in head-on situations.

Table 1. Example data of a two-ship head-on on open waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	
SHIP 1	5	0	-5	0	10
SHIP 2	-5	0	5	0	10

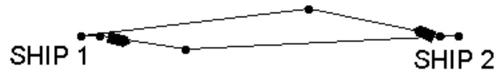

Figure 1. Simulation result for two-ship head-on on open waters

5.2. Crossing situation involving three ships on open waters

Example data of a three-ship crossing encounter on open waters is presented in *Table 2.* Simulation result is presented in *Figure 2.* Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=18.0° E and y_0=56.0° N.

Table 2. Example data of a three-ship crossing on open waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	
SHIP 1	-5	-5	5	5	14
SHIP 2	5	0	-5	0	10
SHIP 3	0	-5	0	5	10

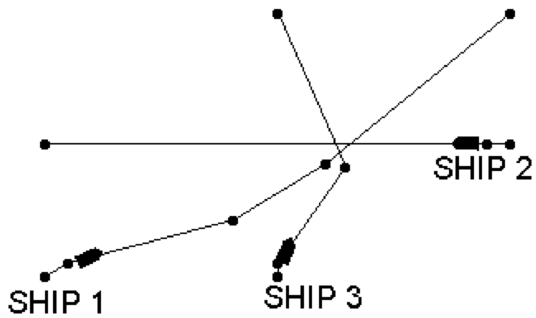

Figure 2. Simulation result for three-ship crossing on open waters

In this scenario ship 2, having no other ships on her starboard, is prioritised and thus doesn't have to perform any manoeuvre. Ship 3 should give way to ship 2 only and makes it so by a single starboard course change. Ship 1 has both ship 2 & 3 on her starboard and must give them way. To achieve that a two-phase starboard course change is performed.

5.3. Encounter of four ships on open waters (including crossing and overtaking)

Example data of a four-ship encounter (including crossing and overtaking) on open waters is presented in *Table 3*. Simulation result is presented in Figure 3. Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=18.0° E and y_0=56.0° N.

Table 3. Example data of a four-ship encounter on open waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	
SHIP 1	-5	-5	5	5	14
SHIP 2	0	-5	0	5	10
SHIP 3	5	0	-5	0	10
SHIP 4	7	0	-7	0	15

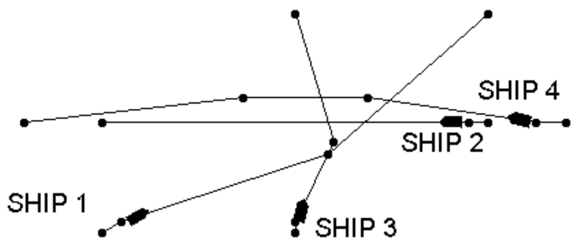

Figure 3. Simulation result for four-ship encounter on open waters

This scenario is based on the previous one, with the additional ship 4 overtaking ship 2. In this situation ship 4 must perform a starboard course change. The only difference in behaviour of ships 1-3 is that ship 1 performs earlier, however one-phase, starboard manoeuvre to avoid collision also with ship 4.

5.4. Head on situation involving two ships on restricted waters

Example data of a two-ship head-on encounter on restricted waters is presented in *Table 4*. Simulation result is presented in *Figure 4.* Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=16.44° E and y_0=56.71° N.

Table 4. Example data of a two-ship head-on on restricted waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	
SHIP 1	-6	-14	6	14	10
SHIP 2	8	13	-10	-15	10

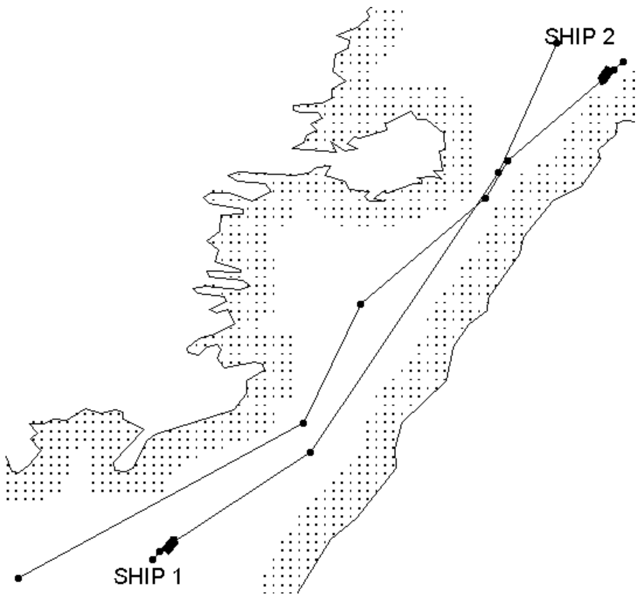

Figure 4. Simulation result for two-ship head-on encounter on restricted waters

In this scenario both ships perform starboard course changes to avoid collision, while keeping a safe distance from the landmass and shallow waters (dotted area) throughout the passage.

5.5. Crossing situation involving three ships on restricted waters

Example data of a three-ship crossing encounter on restricted waters is presented in *Table 5*. Simulation result is presented in *Figure 5*. Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=14.84° E and y_0=56.01° N.

In this scenario ship 1 changes its course to avoid collision with an island. Ship 2 gives way to ship 1 by altering its course to starboard. Ship 3 manoeuvres to starboard to avoid collisions with both ship 1 and the landmass.

Table 5. Example data of a three-ship crossing on restricted waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	

SHIP 1	3	9	-4	-5	10
SHIP 2	-5.8	-5	2.5	12.5	10
SHIP 3	4.5	4.5	-6	12	10

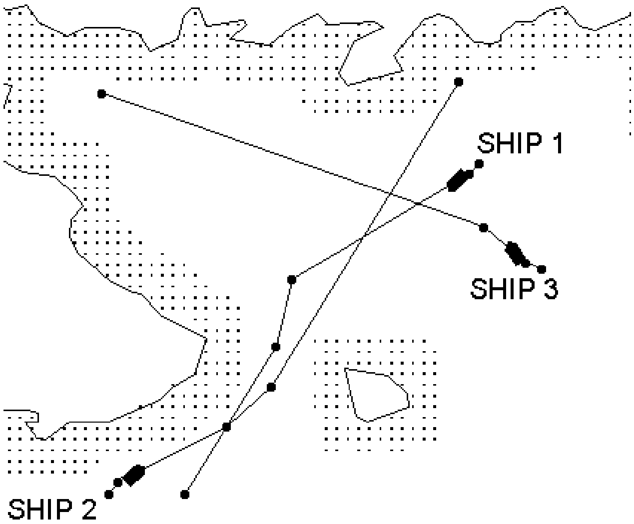

Figure 5. Simulation result for three-ship crossing encounter on restricted waters

5.6. Encounter of four ships on restricted waters (including crossing and overtaking)

Example data of a four-ship encounter (including crossing and overtaking) on restricted waters is presented in *Table 6.* Simulation result is presented in *Figure 6.* Cartesian virtual coordinates in the example are given in nautical miles with centre of the coordinate system in x_0=15.8° E and y_0=56.0° N.

Table 6. Example data of a four-ship encounter on open waters

	Origin		Destination		Speed [kn]
	x [Nm]	y [Nm]	x [Nm]	y [Nm]	
SHIP 1	-12	8	10	-9	10
SHIP 2	-12	6	12	-6	10
SHIP 3	8	6	-14	5	10
SHIP 4	9	8	-14	3	14

In this scenario all ships manoeuvre to avoid collisions with each other and the islands. Ship 1 and ship 2 manoeuvre to their starboard to avoid collisions with the islands, while leaving enough room for ships 3 & 4 to pass safely. Ship 3 manoeuvres to her port boards to avoid collisions with the islands while keeping right from ships 1 & 2. Ship 4 changes course starboard at first to perform overtaking of ship 3, then bypasses the islands by a port board manoeuvre. Additionally ship 1 gives way to ship 2 being on her starboard.

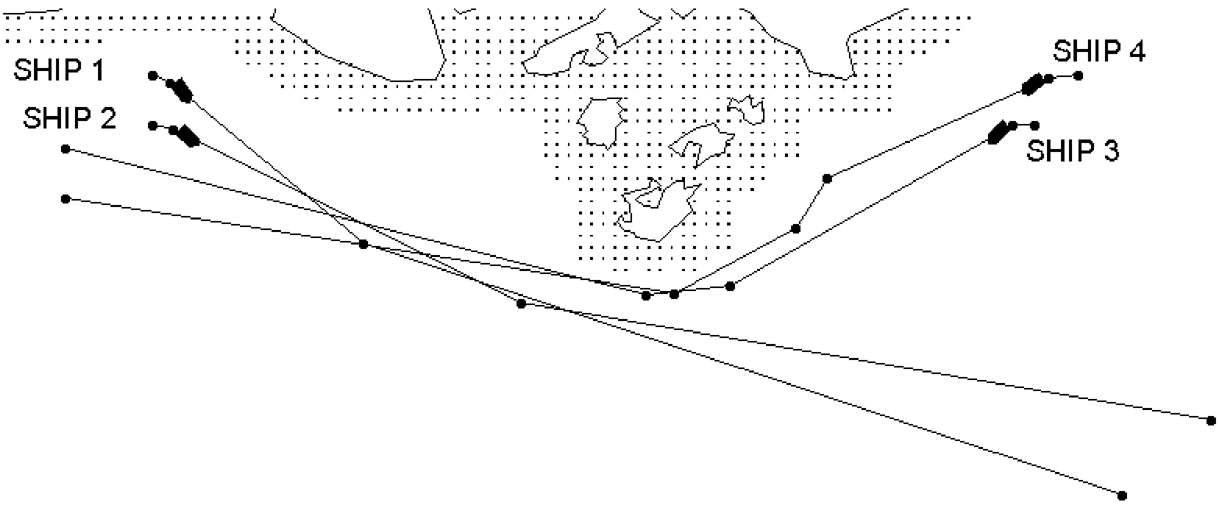

Figure 6. Simulation result for four-ship encounter on restricted waters

6. Summary and conclusions

In the paper the authors have described a newly designed and implemented improvement to the evolutionary sets of cooperating trajectories method, which one of them already proposed before. 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 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 5. 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. Possible future plans of method's development include:

- expanding the optimization model and evolutionary algorithm towards a wider set of criteria (multicriteria optimization),
- designing methods supporting Traffic Separation Schemes (TSS).

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