A Competitive Multipopulation Evolutionary Algorithm for Ship Trajectory Planning

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Abstract. Determining the optimum trajectory for a ship between its current position and the assumed target point, done taking into account navigational situations which the ship is to face when covering this trajectory, was the subject of numerous publications but has not been finally solved yet. The authors propose to determine the optimum and safe ship trajectory using a competitive multipopulation evolutionary algorithm. The proposed algorithm will also allow the trajectory to be corrected depending on a current navigational situation, for instance the appearance of collision threat. Practical application of the algorithm would considerably relieve navigator's work, and contribute to the increase of safety at sea and reduction of ship operation costs.

1 Introduction

International cargo of all European Union countries is mainly delivered using water transport [1]. A similar tendency is observed all over the world, which results in considerable increase of sea traffic. All this, along with resultant decrease of sailing safety, makes the sea navigation more and more difficult [10]. The sailing requires, first of all, determining the ship trajectory which avoids prohibited areas, such as lands, shallow waters, and areas excluded from sailing, and takes into account navigational constraints, such as water lanes. Meteorological forecasts make it possible to detect areas of unfavourable weather conditions that affect the safety level. Consequently, the process of ship trajectory determination has to take into account also the presence and motion of those areas. The determined trajectory is a compromise between the shortest trajectory and the necessity to avoid prohibited areas and those worsening the safety of sailing. When sailing between consecutive turning points of the determined trajectory the ship can meet other objects, such as ships and/or icebergs, which can be a source of collision threat. In this situation a correction is to be made to modify the earlier planned route. Depending on the applied method and techniques, the problem of ship control at sea was discussed in different ways, but has not been finally solved yet. The article presents an evolutionary algorithm which can be used both for determining the initial ship trajectory and its further modifications.

2 Modelling of the navigational environment

The trajectory of the ship sailing in the marine navigation environment has to avoid static and dynamic constraints which can be found on its way. The static constraints include lands, shallow waters, water lanes, and areas such as fisheries which are excluded from sailing. The dynamic constraints include other ships, areas of bad weather conditions, and icebergs.

The lands and shallow waters are defined using polygons in a way identical to the format used in electronic maps. A more detailed description of the adopted model of lands and shallow waters can be found in [4] and [8]. Additionally, these objects are surrounded by prohibited areas having the width at least equal to the assumed safe distance (Figure 1). Such object as fisheries, which are the areas excluded from sailing, are also defined using polygons.

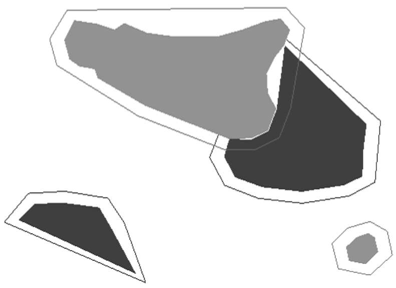

Figure 1. Adopted model of lands and shallow waters.

The ship trajectory in the regions of intensive navigational traffic is limited by a so-called water lane, usually marked by navigation marks and most often consisting of two channels inside which the motion is only possible in one direction. The Gdanska Bay, with the water lanes existing in this area, is shown in Fig. 2a.

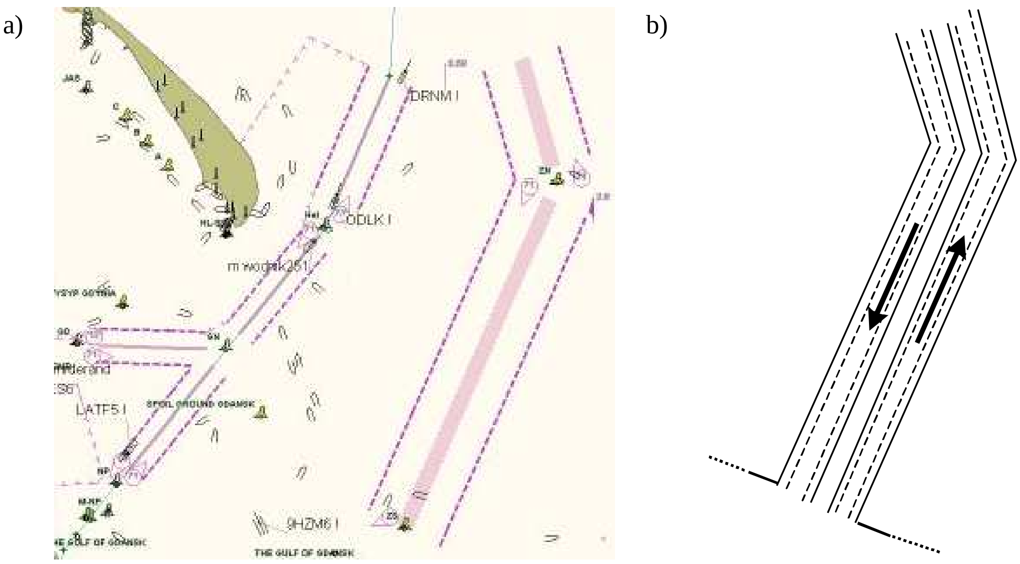

Figure 2. Water lanes: a) in the Gdańska Bay (source: VTS Gdańsk), b) water lane model.

In order to determine the passage trajectory which follows the water lane, it is modelled for the evolutionary algorithm as two independent channels for both directions of the traffic. Additionally, to determine the trajectory of ship passage through a channel, preferred traffic lanes, marked as dashed lines in Fig. 2b, are selected. At the same time, when defining the model of the water lane for the evolutionary algorithm, perpendicular lines starting from the left and right edge of the water lane are introduced. Their use makes it impossible for the evolutionary algorithm to determine the passage trajectory which would omit the water lane.

The ship sailing in the marine environment can approach other objects, such as storm areas which can worsen general safety of sailing, or objects like strange ships or icebergs, being a possible source of collision threat. Around the storm areas and icebergs octagonal areas are defined which are referred to as the domains. The domain of the iceberg excludes the area covered by it from the space in which the safe trajectory is searched. Entering the storm domain area reduces the safety of sailing. Principles of their creation and dimensioning are given in [5, 6, 9].

The approached ships are modelled using hexagonal areas referred to as strange ship domains. A sample shape of this domain is shown in Fig. 3a. When determining the safe trajectory we should check whether it avoids all domain areas. The trajectory which breaks into the area of a domain cannot be considered safe.

The rules of the nautical road formulate the principles governing the passing of ships. The basic principle says that the ships on the left side are to give way. A preferred way of passing is passing behind the stern. The asymmetric shape of the domain will prefer solutions which are in accordance with the rules of the nautical road when determining the safe passing trajectory for the ship [11].

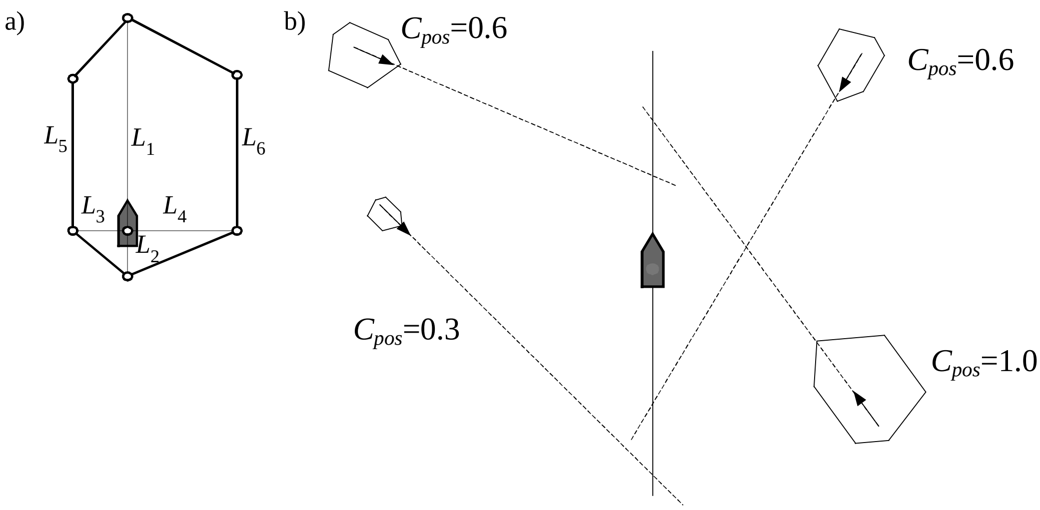

Figure 3. Strange ship domain: a) domain shape, b) scaling factor depending on the position of the strange ship with respect to the own ship.

For the sailing ship the longitudinal dimension of domain L_1 can be determined from formula:

$$L_1 = \left(L_j + D_b + \left(V_0 + V_{RELj}\right)T_{bm} + HM + U\right)R \cdot C_{pos} \quad (1)$$

where:

L_j - ship length expressed in [Mm] (for a strange object detected by the radar system ARPA it is assumed as equal to the length of the own ship L),

D_b - maximum closure distance,

V_o·- speed of the own ship,

V_{REL}·- relative speed of the strange ship,

T_{bm}- time of the safe manoeuvre,

HM - coefficient depending on sea conditions,

U - ship position error,

R - scaling factor depending on the type of water region (the following values were assumed: open sea *R*=1; harbour approach *R*=0.8; narrow channel *R*=0.2),

C_{pos} – scaling factor depending on the position of the approached strange ship.

The remaining dimensions of the domain (L_2, L_3, L_4, L_5, L_6 Figure 3a) are determined as parts of the basic dimension L1. Their detailed description can be found in [9].

The ship domain defines the prohibited area in the space in which the ship trajectory is determined. In an extreme case when the traffic is intensive and the number of sailing objects is large, a situation may occur in which the entire space of the searched solutions is covered by the domains. Therefore it is advisable to introduce a mechanism which will reduce dimensions of the domains for objects with which the collision is less likely to occur. This role is played by the scaling factor C_{pos} which takes different values depending on where the approached ship is with respect to the own ship position. The principle of scale factor selection is illustrated in Figure 3b. For objects situated on the left side, i.e. those who are obliged to give way according to the rules of the nautical road, the coefficient C_{pos} takes smaller values. Its value is also affected by whether the course of the approached object crosses the analysed trajectory in front of the bow or behind the stern of the own ship.

3 Evolutionary algorithm

Determining and correcting the ship trajectory is done using a competitive multipopulation evolutionary algorithm (WKAE - abbreviation of the Polish name). When constructing the algorithm it was assumed that the ship trajectory is defined in the form of a broken line, with turning points as vertexes. Additionally, each individual trajectory segment is labelled with the speed at which the ship is to cover this segment. The first turning point is the initial position of the ship and the last turning point is the target of the trip. A detailed description of the adopted construction of the chromosome can be found in [6] and [8].

The ship trajectory is evaluated using the fitness function, created as the sum of the safety costs and the economic costs:

$$K_C(TP) = K_B(TP) + K_E(TP) \quad (2)$$

where: K_C – total cost connected with covering the trajectory, K_B - safety costs connected with the distance to the constraints, K_E - economic costs connected with the length of the trajectory and the number of turning points. A detailed description of the here adopted fitness function can be found in [8].

A general principle of action of an evolutionary algorithm bases on cyclic processing of the population of solutions with the aid of generic operators, such as crossing and mutation [2]. A fundamental disadvantage of the classical evolutionary algorithm is the problem with obtaining repeatable results. In order to improve the reliability and repeatability of the obtained solutions, an evolutionary algorithm is proposed, the structure of which is shown in Fig. 4. The WKAE is composed of two algorithms the solutions of which, obtained in the evolution process, compete with each other. The final solution is that evaluated as better fitting the assumed evaluation criteria.

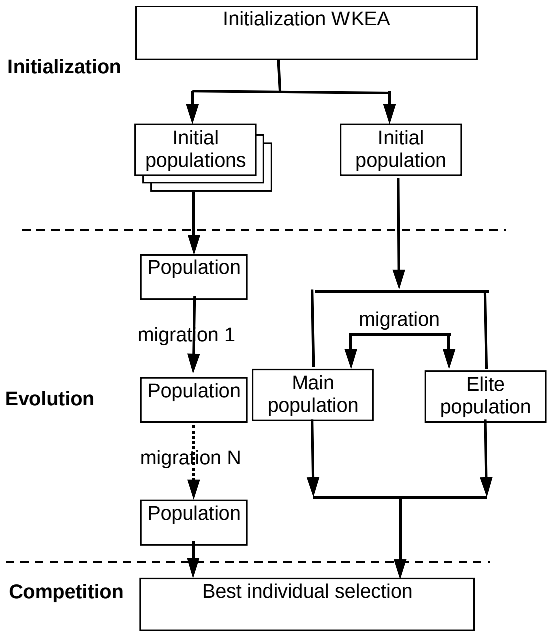

Figure 4. Structure of the competitive multipopulation evolutionary algorithm.

The first competing algorithm is started a number of times, with the best solution from the previous start being introduced to the processed population. The migration is done with some experimentally adjusted delay.

The second algorithm contains two populations in its structure. They are the main population and the elite population. The elite population consists of best fitted individuals from the initial population. The main population contains the remaining, worse fitted individuals from the initial population [3]. These two populations evolve independently, but the migration of individuals between them is possible. The migration takes place when the fitness of an individual in the main population is higher than the average fitness in the elite population. The level and time of migration delay were selected experimentally. The base population is responsible for exploration of the space of problem solutions, while the elite population explores the vicinity of the best solutions obtained from the main population.

The individuals for the initial population are generated in a random way. As a result, the majority of the trajectories represented by the individuals include segments that violate static constrains or reveal loops. Additionally, some fragments of the trajectory may turn out impossible for practical execution, for instance, due to excessive course change at a turning point, or too small length of the trajectory segment. The initial population for the navigational situation with two lands, the shallow water, and a water lane is shown in Fig. 5a.

In order to improve the efficiency of WKAE operation, the initial populations are subject to preliminary processing [2]. The first processing step focuses on removing loops in the trajectories by the repair operator (Figure 5b). The next modification of the genetic material is smoothing the trajectories composing the initial population (Figure 5c). Avoiding static constraints was obtained by introducing additional turning points which lead the ship along the borders of the prohibited areas surrounding the lands and shallow waters, or along the relevant traffic lanes of the water lanes (Figure 5d).

Along with the above discussed repair operator, specialised versions of the operators were used to improve the efficiency of algorithm operation:

- action of the basic mutation operator was made dependent on the angle between the two segments linking each other at the examined turning point:
  - when the angle is large, the gene is removed provided that the new trajectory does not violate navigational restrictions,
  - when the angle is medium-sized, the vertex is shifted randomly in the direction which smoothes the trajectory, the operation is done provided that the trajectory remains safe,
  - a turning point is added when the angle between the adjacent segments is small, the vertex is shifted to a randomly selected position on the first ray of the angle and the new point is placed at a random position on the second ray
- global mutation, which shifts randomly the turning point within the entire area of the analysed navigational situation,
- adding a random turning point,
- speed mutation, which modifies the speed at a randomly selected trajectory segment to make it possible to avoid contact with dynamic constraints,
- operator executing the avoidance manoeuvre function, which introduces turning to the left or right side to avoid collision with the approaching ship,
- crossing, using the genetic material from two parent trajectories this operator creates offspring individuals. The crossing points on parent chromosomes are selected in a random way from among the crossing points which do not lead to the violation of restrictions in the offspring individuals. Then the individuals exchange the cut-off parts thus creating the offspring.

In all cases the change introduced by a given operator for the individual is only possible when it does not lead to the violation of restrictions.

During the operation of the algorithm the operators are selected randomly. The probability that a given operator will be selected changes with time within the assumed limits depending on the effect of its operation on the quality of earlier processed trajectories. The effects of operation of the developed genetic operators are shown in Fig. 5e in which we can see the population from Fig. 5d after one generation. Figure 5f presents the population after successive 20 generations.

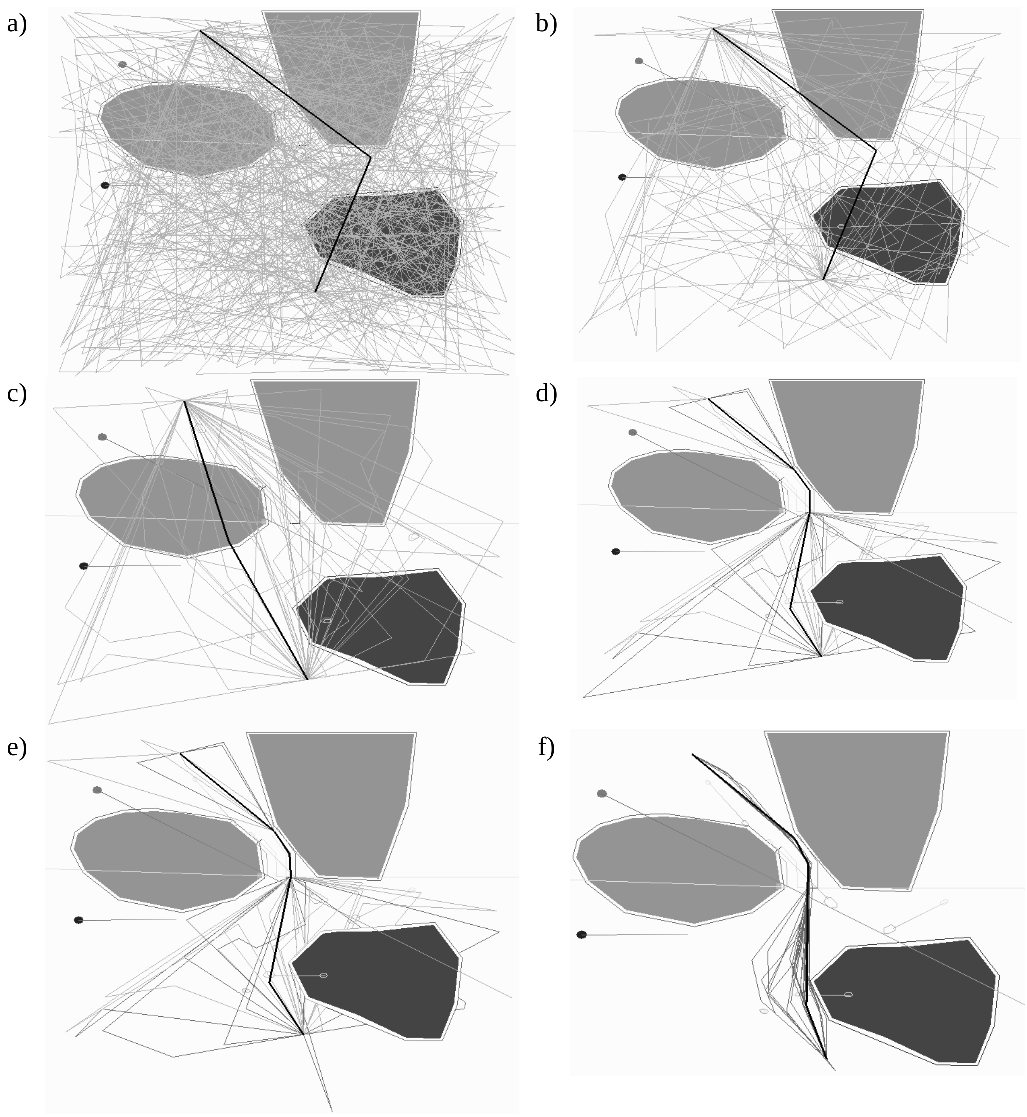

Figure 5. The operation of genetic operators a) randomly created initial trajectory population, b) population after loop removal, c) population after smoothing, d) population after repair oriented on avoiding static constraints, e) population after single action of all genetic operators, f) population after 20 cycles of operation of genetic operators.

4 Experimental investigations

The experimental investigations were carried out using the sea environment simulator described in [5] and [7]. The analysed navigational situation included the land and nine approaching ships

(Figure 6). The ship No. 2 is the source of direct collision threat. Solutions obtained in five successive starts of the algorithm are shown in Fig. 7.

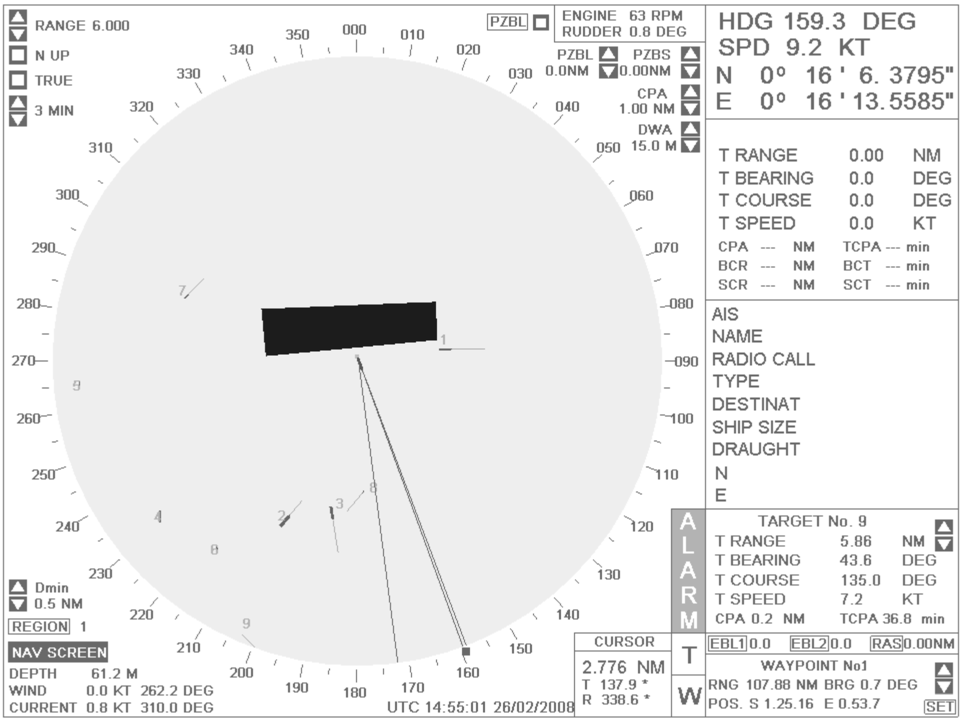

Figure 6. Navigational situation.

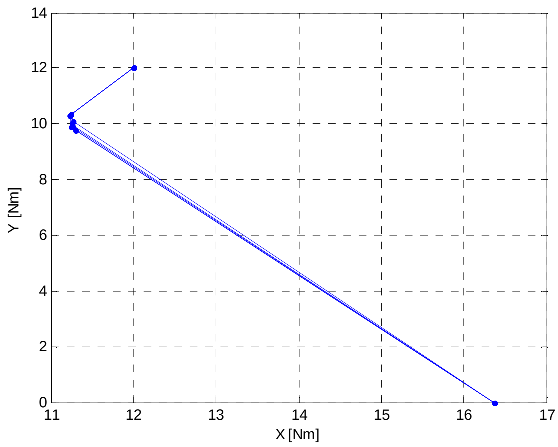

Figure 7. Solutions obtained after 5 consecutive starts of the algorithm.

The ship moving along the trajectory determined by WKAE performs turning to the right to avoid the approaching ship No. 2. The course of the simulation is shown in Figure 8. The trajectory determined by WKAE made it possible to pass safely the approaching ships.

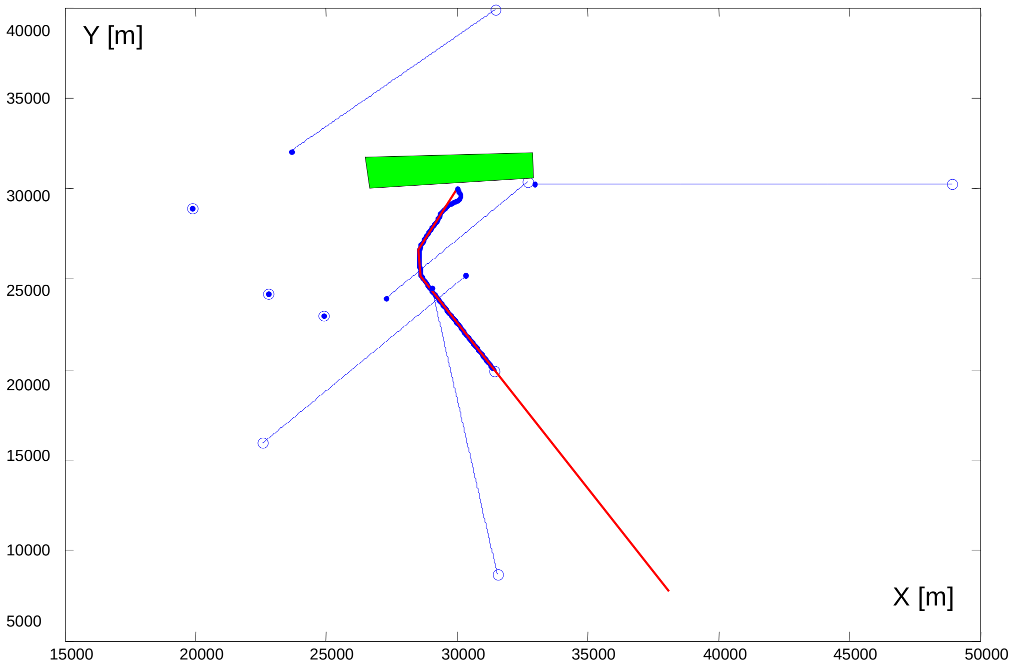

Figure 8. Simulation in which the ship follows the trajectory determined by WKAE.

5 Conclusions

Practical application of the competitive multipopulation evolutionary algorithm can considerably relieve navigator's work, in particular calculations oriented on determining the ship trajectory and anti-collision manoeuvres. An essential advantage of the system is the improved repeatability of the obtained results. The algorithm can also contribute to the increase of safety at sea, and to the reduction of ship operation costs.

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