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Multi-criteria ACO-based Algorithm for Ship's Trajectory Planning

A. Lazarowska
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The paper presents a new approach for solving a path planning problem for ships in the environment with static and dynamic obstacles. The algorithm utilizes a heuristic method, classified to the group of Swarm Intelligence approaches, called the Ant Colony Optimization. The method is inspired by a collective behaviour of ant colonies. A group of agents - artificial ants searches through the solution space in order to find a safe, optimal trajectory for a ship. The problem is considered as a multi-criteria optimization task. The criteria taken into account during problem solving are: path safety, path length, the International Regulations for Preventing Collisions at Sea (COLREGs) compliance and path smoothness. The paper includes the description of the new multi-criteria ACO-based algorithm along with the presentation and discussion of simulation tests results.

1 INTRODUCTION

The problem of collision avoidance is an up-to-date and dynamically developing research topic.

Control systems, providing opportunity of safe control of an object in a dynamic environment, enabling collision avoidance of both stationary and moving obstacles, occurring in the vicinity, are applied in autonomous mobile robots, unmanned vehicles, aircraft anti-collision systems and also marine control systems, called Guidance, Navigation and Control (GNC) systems.

Currently, the existing ship collision avoidance systems determine the risk of collision with the use of parameters such as the Closest Point of Approach (CPA) and the Time to the Closest Point of Approach (TCPA), indicate the collision threat by appropriate alarm and allow to check the effects of the planned manoeuvre (the trial manoeuvre function of an Automatic Radar Plotting Aid - ARPA), but do not give proposals of safe course or speed alterations.

The development of the ship's safe control system, enabling automatic determination of a safe trajectory of the ship, is still a current and important research problem. The solution of this issue can then be extended for application to other mobile objects (airplanes, unmanned vehicles, mobile robots).

In order to obtain the safe and optimal trajectory of a ship a variety of deterministic and heuristic optimization methods are proposed in the literature. Among the most recent proposals the following methods should be mentioned: the A* algorithm (Naeem et al. 2012), the Ant Colony Optimization (Escario et al. 2012, Tsou & Hsueh 2010), the cooperative path planning (Tam & Bucknall 2013), the differential games (Lisowski 2016b), the dynamic programming (Lisowski 2016a), the fast marching method (Liu & Bucknall 2015), the fuzzy logic approach (Mohamed-Seghir 2016, Perera et al. 2011), the genetic algorithm (Tam & Bucknall 2010, Tsou et al. 2010), the neural networks (Ahn et al. 2012, Simsir et al. 2014) and the potential field method (Xue et al. 2011). In the last few years a new approach emerged, based upon the use of auto-negotiation of manoeuvres (Hornauer & Hahn 2013, Szłapczyńska 2015). The multi-criteria optimization methods are also present in the current literature (Szłapczyński & Szłapczyńska 2012, Śmierzchalski et al. 2013).

The problem is a complex optimization task, so it is very difficult to develop a method, applicable in commercial solutions, that will take into account all of the constraints and process requirements, such as static and dynamic obstacles, fulfilment of the International Regulations for Preventing Collisions at Sea (COLREGs), near-real time operation.

The aim of the research presented in this paper is to develop an algorithm for ship's safe trajectory planning, applicable in a GNC system, utilizing a multi-criteria ACO-based algorithm.

2 SHIP'S TRAJECTORY PLANNING

Figure 1 shows a diagram of an GNC system, where the ship's safe trajectory planning algorithm is applied in the Trajectory Generator (TG) module. Besides the different sensors, a computer with an advanced optimization algorithm, constitutes the basic component of a TG. The TG computes a safe, optimal trajectory based upon the motion data (position and velocity) of an own ship (OS) and other vessels from the Navigation System and passes the results to the Motion Control System.

The ship's safe, optimal trajectory planning problem can be regarded as an optimization task. The optimization criteria that should be taken into account during problem solving include: path safety (not exceeding static and dynamic navigational constraints), path length, COLREGs compliance and path smoothness (the smallest course alterations).

Due to the need to take into account several criteria, when searching for the safe and optimal trajectory of the ship, the task should be regarded as a multi-criteria optimization problem.

3 MULTI-CRITERIA ACO-BASED ALGORITHM

It was decided, that the Weighted Objectives Method will be applied as a multi-criteria optimization approach. The idea of this method is to transform a multi-criteria optimization into a single criterion optimization, by an application of a fitness function constituting a weighted sum of different criteria, as in Equation 1.

$$F(x) = \sum_{i=1}^{k} w_i f_i(x) \qquad (1)$$

The fitness function is than evaluated as in a single criterion optimization task.

In the research presented in this paper a fitness function applied to solving ship's trajectory planning problem is defined by Equation 2.

$$fitness(p) = w_1 \cdot safety(p) + w_2 \cdot length(p) + w_3 \cdot smoothness(p) + w_4 \cdot rules(p) \qquad (2)$$

The safety criterion *safety(p)* evaluates the safety of the trajectory. It is checked, whether the trajectory does not intersect static obstacles (lands, shallows) and does not cause collision with other ships occurring in the vicinity of an own ship.

The criterion *length(p)* is calculated as a length of the minimal trajectory (a line segment joining an own ship actual position (the starting waypoint) to the final waypoint) divided by a length of the evaluated trajectory.

The *smoothness(p)* criterion evaluates the smoothness of the trajectory, that means the values of course alterations at consecutive stages of the trajectory. When the course alteration is less than 15 degrees or more than 60 degrees, the calculated value of this criterion fulfilment for the evaluated path is reduced by a predefined penalty factor.

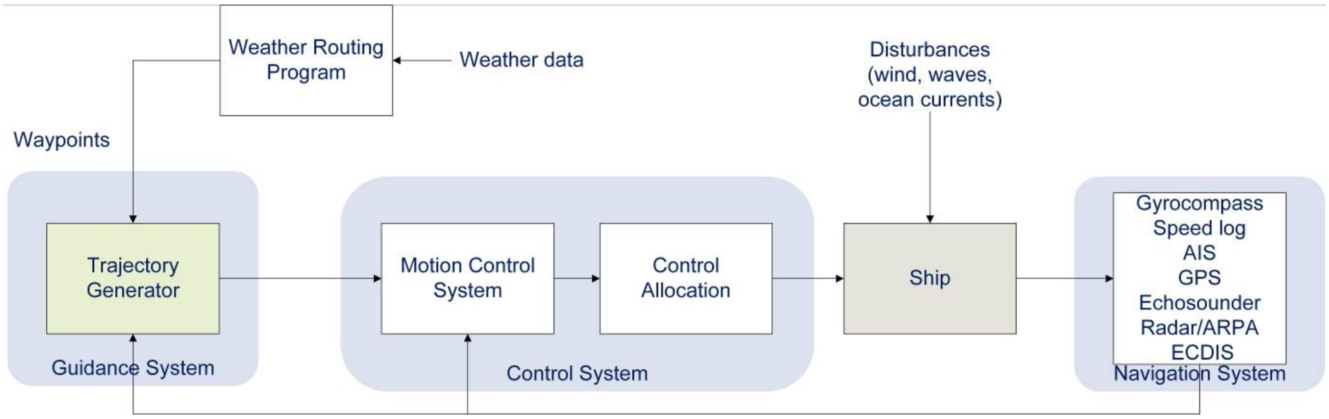

Figure 1. GNC system diagram based upon (Fossen 2011).

The *rules(p)* criterion is applied to evaluate the COLREGs compliance of the trajectory. When the evaluated trajectory consists of a manoeuvre to the port side, the value of this criterion fulfilment for the evaluated path is reduced by a predefined penalty factor.

Multi-criteria ACO-based algorithm for ship's safe trajectory planning, presented in this paper, is a development of an algorithm presented in (Lazarowska 2013). The previous version was developed to solve a problem regarded as a single criterion optimization task. The fitness function applied there was defined as the length of the trajectory. The operation principle is similar for both versions of the algorithm: single and multi-criteria approach. The difference is in the fitness function applied to find the final solution.

Input data concern motion parameters of all of the ships taking part in an encounter situation, their courses, speeds, bearings and distances from an own ship. The Ant Colony Optimization method is applied to calculate a set of solutions (trajectories). These solutions are then evaluated with the use of a specified fitness function and a solution characterized by the highest value of the path fitness constitutes the final solution (trajectory).

The first step of the algorithm is the input data reception from the Navigation System. Based upon the received information, in the next step relative courses, speeds and bearings of target ships (TSs) are calculated. After that, the dangerous TSs check procedure is executed. It is applied to evaluate, whether the TS constitutes a dangerous object (obstacle). A TS is considered as a dangerous object, when it intersects its course with the course of an own ship.

In the next step a construction graph is built, taking into account both static (lands, shallows) and dynamic (TSs) constraints. The graph vertices constitute possible own ship positions.

Then, the ACO calculations are performed. In this procedure, at first ACO parameters, such as: the pheromone trail amount on all vertices (τ_0), the α and β coefficients used in the formula calculating ant's next move probability, the pheromone evaporation rate (ϱ), the number of ants, the maximum number of ant's steps and the number of iterations, are initialized. Afterwards, two steps are repeated for a defined number of iterations: the solution construction procedure and the pheromone trail update procedure.

In the solution construction procedure every ant builds its path from the starting vertex of the graph (current position of an own ship) to the ending vertex (the defined final point of the trajectory). At every step an ant chooses the next own ship position (the vertex on the graph) with the use of the action choice rule, which works similarly to the roulette wheel selection procedure used in the evolutionary algorithms. The probabilistic choice of the next vertex depends on the value of the parameter called the pheromone trail on the neighbouring vertex and the heuristic information called visibility. The visibility is defined as the inverse of the distance between the current vertex and the neighbouring vertex.

The pheromone trail update procedure is composed of two stages: the pheromone evaporation and the pheromone deposit. The function of the pheromone evaporation is to reduce the value of pheromone trail on all vertices. During the pheromone deposit a certain value of the pheromone trail is added to all vertices belonging to the paths constructed by ants in the iteration. The aim of this mechanism is to increase the pheromone trail value on the vertices constituting parts of the shortest paths, what enhances the probability of their selection by the ants in the subsequent iterations.

Next, trajectories belonging to the set of solutions determined with the use of ACO method, are smoothened in order to receive more optimal paths and evaluated with the use of a fitness function defined by Equation 2. In the last step the solution characterized by the highest value of a fitness function is presented in a numerical and graphical form.

Figure 2 shows the flowchart of the multi-criteria ACO-based algorithm for ship's safe trajectory planning.

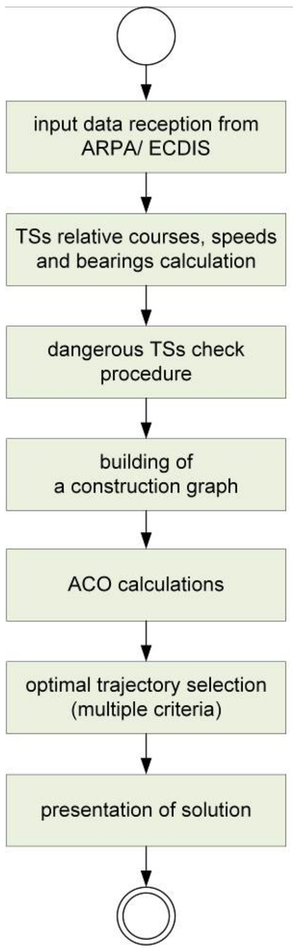

Figure 2. Flowchart of the multi-criteria ACO-based algorithm for ship's trajectory planning.

4 SIMULATION TESTS

The developed algorithm was implemented as a computer program in MATLAB programming language. The MATLAB environment was chosen due to the possibility of using in-built functions for graphical presentation of results. The calculations were run on a PC with Intel Core i5 2.27 GHz processor and 32-bit Windows 7 Professional operating system.

Two representative test cases were chosen for the presentation in this paper: with two TSs and with four TSs. Motion parameters of the ships taking part in test cases are listed in Tables 1 and 3. Figures 3 – 5 and 7 – 9 show graphical results – the trajectory of an OS along with positions of TSs at consecutive stages of their movement. Tables 2 and 4 present numerical results of test cases.

Table 1. Test case 1 motion parameters of all ships.

Setting Ship	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	19.0	–	–
1	70	9.0	340	7.0
2	245	9.0	20	6.0

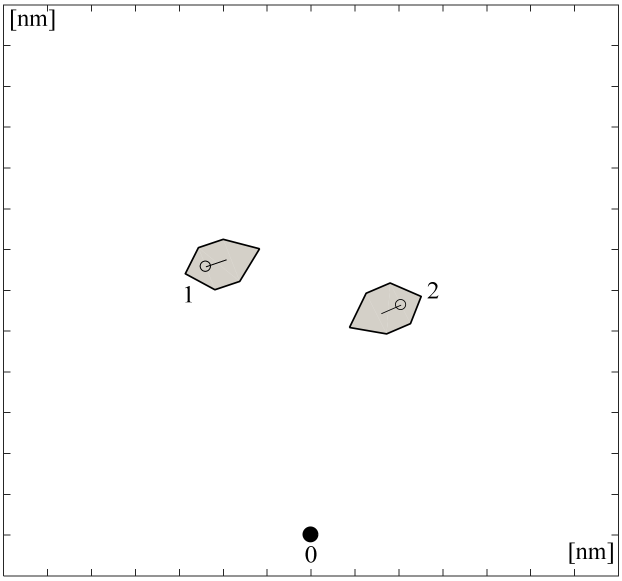

Figure 3. Graphical presentation of test case 1.

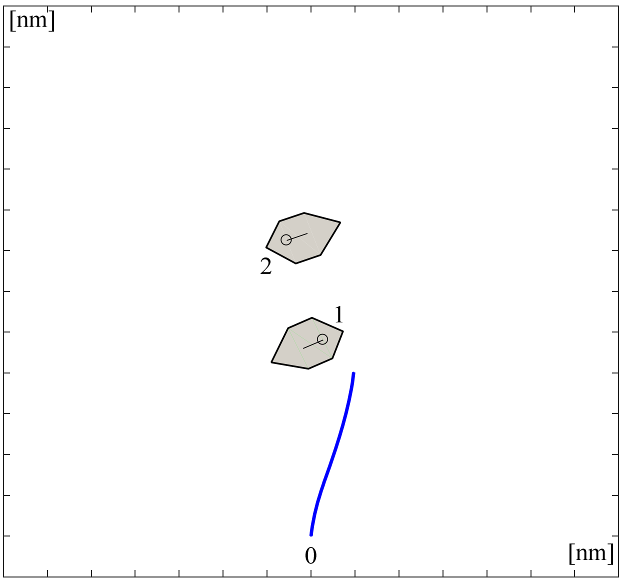

Figure 4. Graphical presentation of test case 1 – OS moving along the trajectory.

The simulation tests were performed taking into account different optimization criteria and constraints: a single criterion: path length and multiple criteria: path length and path safety, path smoothness (angles) and path safety, path smoothness (angles) and COLREGs compliance of the path (rules) and all of the above mentioned criteria. Figures 6 and 10 show the comparison of the OS trajectories calculated by the algorithm for different optimization criteria.

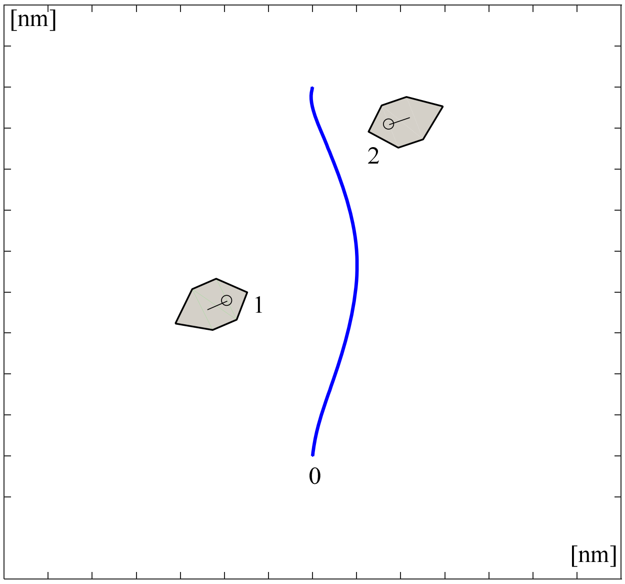

Figure 5. Graphical presentation of test case 1 – OS at the final waypoint.

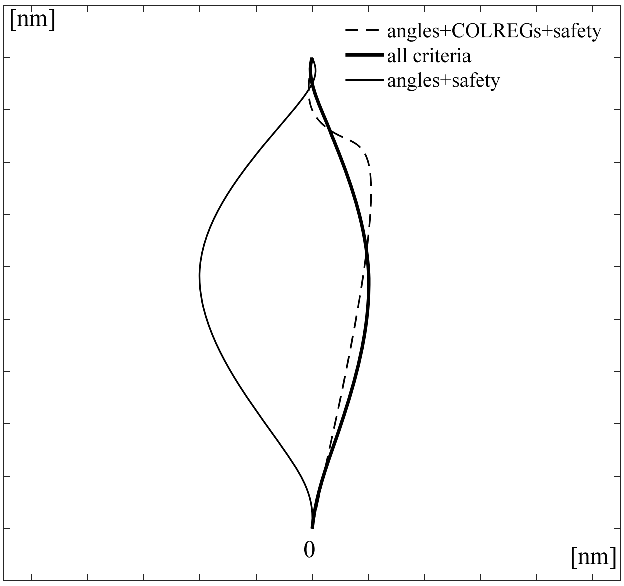

Figure 6. Graphical presentation of test case 1 – trajectories calculated for different optimization criteria.

Table 2. Results of test case 1.

optimization criteria	path length [nm]	path fitness	course alteration [°]	path safety
length	9.42	0.9759	11;25	safe
length+safety	9.42	0.9807	11;25	safe
angles+safety	10.23	1.0000	22;49	safe
angles+rules	9.57	0.9800	8;56;45	safe
all criteria	9.42	0.9852	11;25	safe

Table 3. Test case 2 motion parameters of all ships.

Setting Ship	Course [°]	Speed [kn]	Bearing [°]	Distance [nm]
0	0	20.0	–	–
1	90	10.5	326	7.8
2	270	20.5	46	5.8
3	180	10.0	2	12.4
4	200	17.0	11	5.5

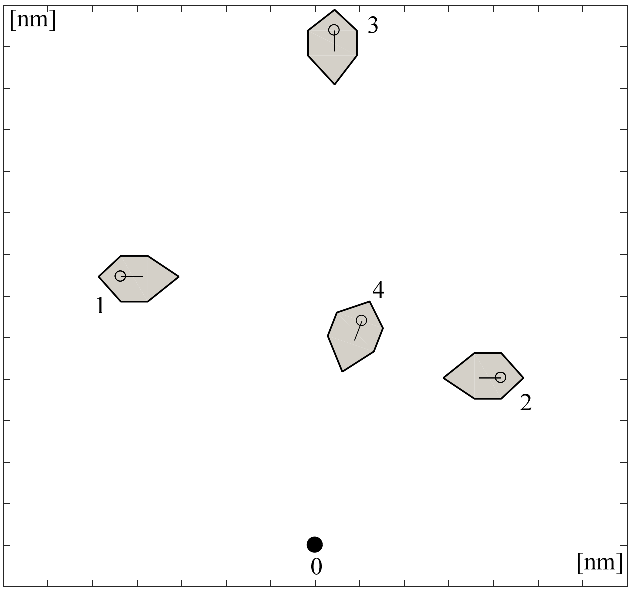

Figure 7. Graphical presentation of test case 2.

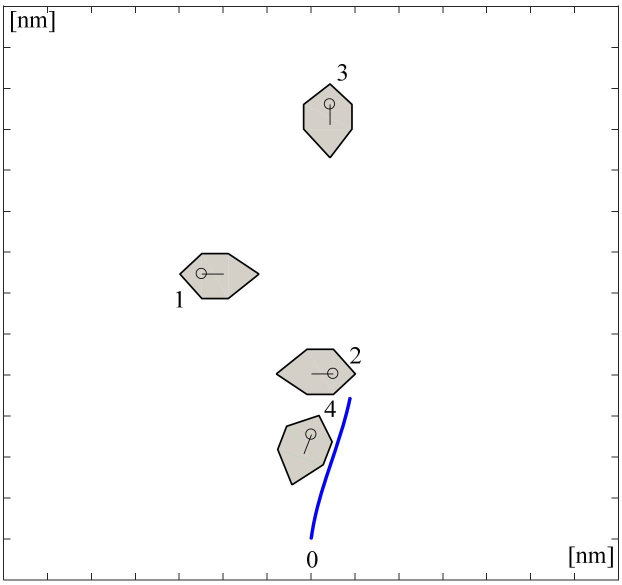

Figure 8. Graphical presentation of test case 2 – OS moving along the trajectory.

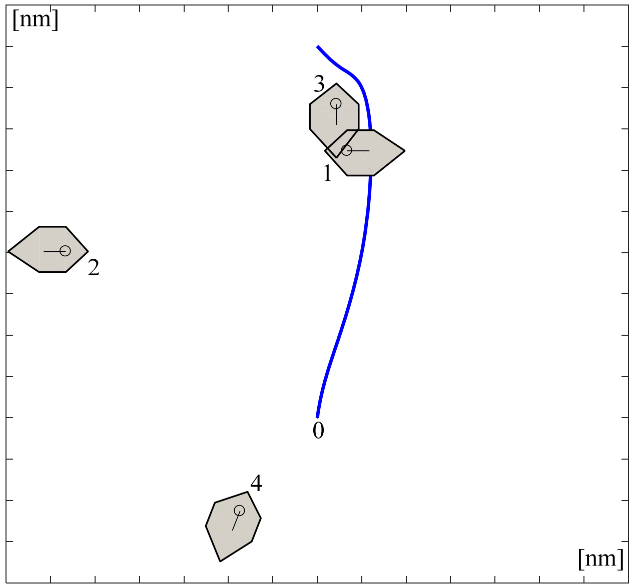

Figure 9. Graphical presentation of test case 2 – OS at the final waypoint.

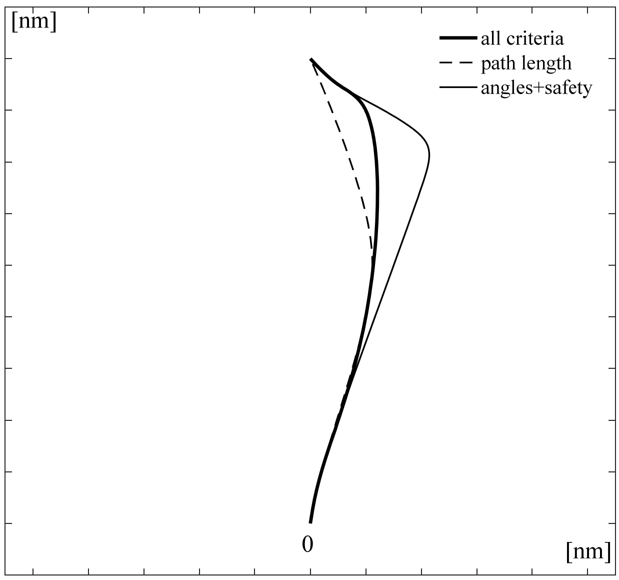

Figure 10. Graphical presentation of test case 2 – trajectories calculated for different optimization criteria.

Table 4. Results of test case 2.

optimization criteria	path length [nm]	path fitness	course alteration [°]	path safety
length	9.31	0.9693	14;14;18	collision
length+safety	9.59	0.9549	14;14;45	safe
angles+safety	10.38	0.9600	16;61	safe
angles+rules	9.59	0.9600	14;14;45	safe
all criteria	9.59	0.9687	14;14;45	safe

5 DISCUSSION AND CONCLUSIONS

In Tables 2 and 4 results of test cases are compared with regard to: path length, fitness function value of the solution, course alterations needed to execute the determined trajectory and safety of the solution.

The multi-criteria approach enables to take different criteria into account: constraints of the process and optimization objectives. Such approach allows to consider the system operator's (navigator's) preferences, which criteria he/she would like to take into account during problem solving.

Different criteria taken into account, as the results of simulation tests indicate, lead to different solutions. The criterion that must be taken into account is the path safety, what is confirmed by the results in Table 4. Including only path length in the fitness function can lead to obtainment of a shorter trajectory, but with a collision point.

To sum up, the multi-criteria ACO-based approach for ship's safe path planning, presented in this paper, enables to solve the considered problem by calculation of a collision-free trajectory of an OS. The method enables taking into account all of the important assumptions and constraints of the process, such as the static (lands, shallows) and dynamic (TSs) obstacles, the COLREGs, optimality of the solution and near-real time of calculations (under one minute). The above mentioned features of the proposed approach allows its application in modern NGC systems. The method presented here can also be applied to other fields, where an obstacle avoidance problem of a moving object in a dynamic environment occur, such as for example the task of mobile robots navigation.

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