Multi-criteria Trajectory Base Path Planning Algorithm for a Moving Object in a Dynamic Environment

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***Abstract*—The paper introduces a new, original approach for the application in robotics and automation. The application concerns a path planning module of an intelligent control system. The marine environment was chosen as an exemplary application area, but the method can also be applied for mobile robots. The presented approach calculates a safe, optimal path for a ship in a dynamic environment, where static and dynamic obstacles occur. The paper includes the background of the presented research, the description of a new method and results of simulation studies. Simulation tests covered simple and more complex scenarios with a few static and dynamic obstacles in the environment. The results proof the problem solving capability of the proposed approach and the potential of its applicability in commercial systems due to short computational time and satisfactory solutions.**

***Keywords*—autonomous systems, intelligent control systems, path planning.**

I. Introduction

The dynamic development of modern soft computing techniques leads to the progress in expert and intelligent systems. Autonomous navigation systems can be classified to this group of systems. Autonomous navigation covers path planning and collision avoidance tasks. Applications of autonomous navigation systems include mobile robots, drones, unmanned surface and underwater vehicles, and ships.

The research presented in this paper was focused on the development of a new, original path planning method for a moving object in a dynamic environment. An exemplary environment, used in this research, is the marine environment. The presented method is used for planning a safe, optimal path for a ship.

Many path planning and obstacle avoidance methods have been proposed in the literature so far. Among the most recent proposals the following approaches should be mentioned: the A* algorithm [1], the Ant Colony Optimization [2], the cooperative path planning [3], the differential games [4], the fast marching method [5], the fuzzy logic [6], [7], the genetic algorithm [8], the neural networks [9], [10] and the potential field method [11]. Among the path planning methods for mobile robots the following approaches should be noticed: the Bacterial Potential Field [12], the Bacterial Foraging Optimization [13], the Virtual Force Field [14] and hybrid approaches: Artificial Bee Colony with Evolutionary Programming [15] and Ant Colony with Immune Network algorithm [16]. The existing path planning methods for ships have been compared in table I.

TABLE I
COMPARISON OF EXISTING PATH PLANNING METHODS

Optimization method	Static obstacle	Dynamic obstacle	Fitness function	Run time [s]	Repeat-ability
A* algorithm	✓	✓	distance	?	✓
deterministic method	✗	✓	course = 30 deg	a few	✓
differential games	✗	✓	min. deflection	a few	✓
fast marching	✓	✓	distance	< 1	✓
fuzzy logic	✗	✓	COLREGs	?	✓
evolutionary algorithm	✗	✓	distance + time	> 200	✗
neural network	✗	✓	?	?	✓
potential field	✓	✓	?	?	✓

Despite these many contributions introduced so far, the issue of path planning is still an open research topic. The problem is a complex multi-criteria optimization task with many constraints and objectives to be taken into account. Therefore, the development of an effective method, returning solution in near-real time, is a very demanding goal.

In this paper a new approach, contributing to the development of autonomous systems, is presented. The method is based upon the author's original approach, utilizing a database of candidate solutions (a base of trajectories) [18].

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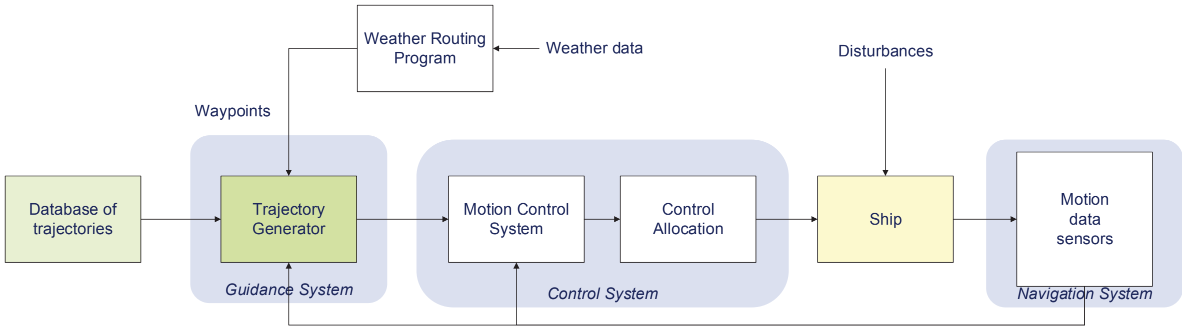

Fig. 1. The Guidance, Navigation and Control system diagram based upon [17].

II. Path Planning in an Intelligent Control System

The development of autonomous systems constitutes an up-to-date trend in the area of expert and intelligent systems. Autonomous navigation of a moving object in a dynamic environment belongs to this area of research. Path planning and obstacle avoidance for drones, mobile robots, aircrafts, ships, unmanned surface vehicles and unmanned underwater vehicles is a present-day issue.

This paper is dedicated to the development of a path planning module, constituting a part of an intelligent control system for ships. However, the presented method can be easily adapted for application in other fields, such as robotics. In the marine environment, an intelligent control system in called a Guidance, Navigation and Control system (GNC). It is composed of three main subsystems:

- the Guidance System, responsible for path planning
- the Control System, responsible for motion control
- the Navigation System, responsible for measurement of motion parameters (ship's positions and velocities).

Figure 1 presents an intelligent control system for ships. The basic component of the path planning module (the Guidance System) is called the Trajectory Generator (TG). An advanced optimization algorithm, constituting the core of the TG, calculates a safe, optimal path for a ship.

The ship's path planning problem can be regarded as an advanced optimization task, where different constraints (static and dynamic obstacles) and different optimization criteria (path length, path smoothness) have to be taken into account. The Motion Control Subsystem executes the safe, optimal trajectory calculated by the TG.

III. Multi-criteria Trajectory Base Algorithm (TBA) for Path Planning

The path planning algorithm is based upon a new, original approach utilizing a database, where candidate solutions are stored. The flowchart of the algorithm is presented in Figure 2. The first step of the algorithm is the calculation of the relative course, speed and bearing of every target ship (TS), based upon the ship's motion parameters measured by the Navigation System.

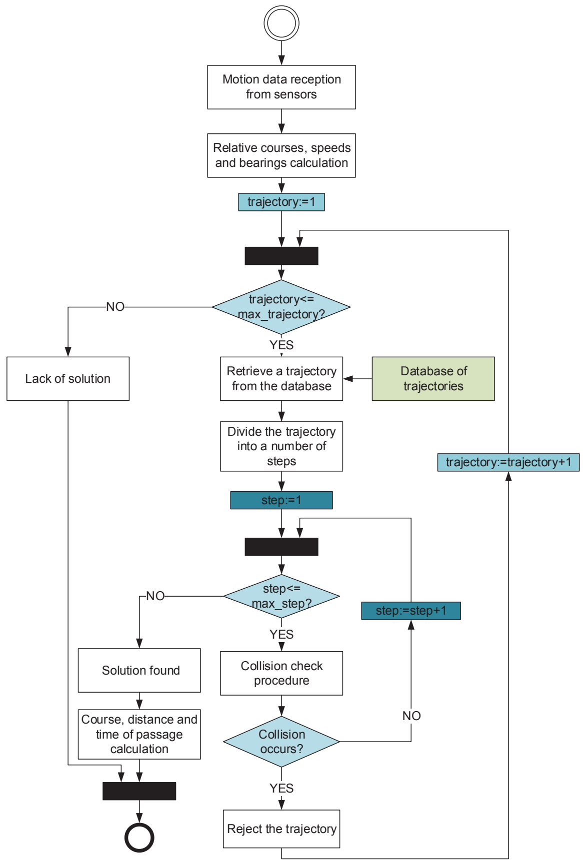

Fig. 2. The Trajectory Base Algorithm (TBA) diagram.

After that, the first candidate solution (trajectory) is retrieved from the trajectory base (the database with candidate solutions) for the collision check procedure. This procedure is applied to evaluate, whether the considered candidate solution (trajectory) violates static and/or dynamic obstacles. If the calculations confirm that the collision occurs, the candidate solution (trajectory) is rejected and the next candidate solution is retrieved from the database for evaluation.

The candidate solutions (trajectories) are sorted in the trajectory base according to the descending order of their fitness function values. The final solution is the solution characterized by the highest value of the fitness function, which does not violate any of the static and dynamic obstacles.

$$f(p) = w_1 \cdot length(p) + w_2 \cdot angles(p) + w_3 \cdot rules(p) \quad (1)$$

The fitness function $f(p)$ (Equation 1) is defined with the use of the Weighted Objectives Method, where w_1, w_2 and w_3 are the weight coefficients for different criteria included in the function. The fitness function is defined as a weighted sum of three criteria: $length(p)$, $angles(p)$ and $rules(p)$.

The $length(p)$ criterion is calculated as the length of the minimal trajectory (a line segment joining the starting waypoint wp_0 and the ending waypoint wp_e) divided by the length of the evaluated trajectory.

The $angles(p)$ criterion penalises the trajectories (the line segments constituting parts of the trajectory), for which the course alterations are less than 15 degrees or exceed 60 degrees.

The $rules(p)$ criterion penalises the trajectories, which do not fulfil the International Regulations for Preventing Collisions at Sea (COLREGs), e.g. if the own ship (OS) executes a manoeuvre to port side, the value of this criterion is reduced by a predefined penalty factor.

In the last step of the algorithm, the final solution is presented in a graphical and numerical form, as shown in section IV - Simulation Tests.

IV. Simulation Tests

In order to prove the problem solving capability of the presented method, the algorithm was implemented as a computer program in MATLAB programming language. The MATLAB environment was used due to the integrated graph-plotting features, which facilitate the graphical presentation of results.

The simulation tests covered simple and more complex scenarios with one and multiple target ships (TSs) and with the occurrence of static obstacles (areas of land, islands). Two representative test cases were chosen for the presentation in the paper. The first one with two randomly distributed areas of lands and four target ships, and the second test case with two islands and three target ships.

Calculations for the test cases were performed with the consideration of different optimization criteria. The fitness function was taking into account the following criteria:

- path length
- values of course alterations
- collision avoidance rules compliance of the trajectory.

The calculations were performed on a PC with the Intel Core i5 2.27 GHz processor, 32-bit Windows 7 Professional operating system.

A. Test Case 1

This simulation scenario includes two static obstacles (islands) and four dynamic obstacles (TSs). The motion parameters describing test case 1 are listed in Table II. Figures 3 to 5 show graphical presentation of test case 1 and the calculated solution (the OS trajectory) along with the positions of TSs at consecutive stages of the ship's movement. Numerical results of test case 1, listed in Table III, include the path length, the fitness function value, input data to the motion control

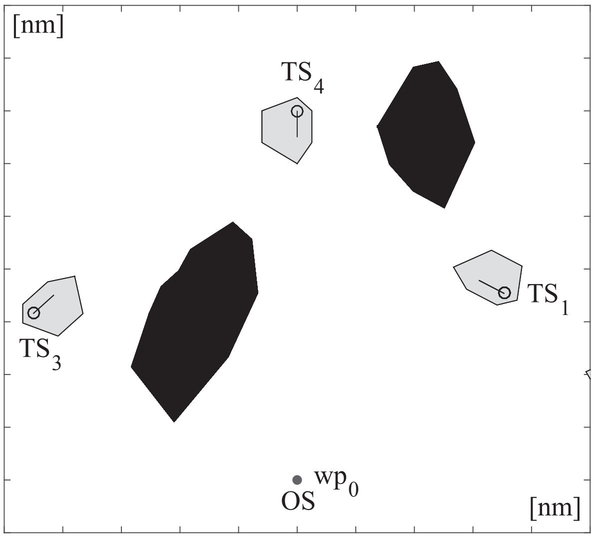

Fig. 3. Graphical presentation of test case 1 – OS at wp_0.

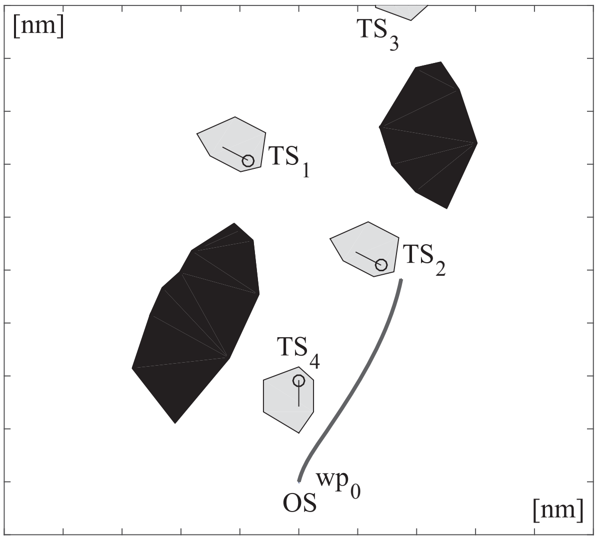

Fig. 4. Graphical presentation of test case 1 – OS moving along the trajectory.

TABLE II
TEST CASE 1 MOTION PARAMETERS OF ALL SHIPS

Ship	Course (deg)	Speed (kn)	Bearing (deg)	Distance (nm)
OS	0	10	-	-
TS_1	300	12	45	5
TS_2	300	12	75	6
TS_3	45	20	305	5.5
TS_4	180	12	0	7

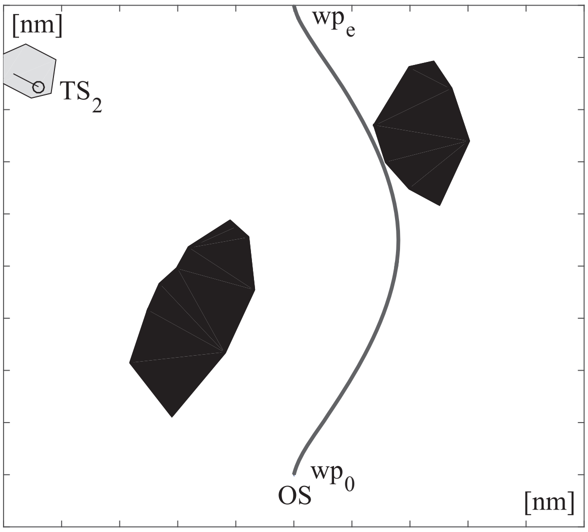

Fig. 5. Graphical presentation of test case 1 – OS at wp_e.

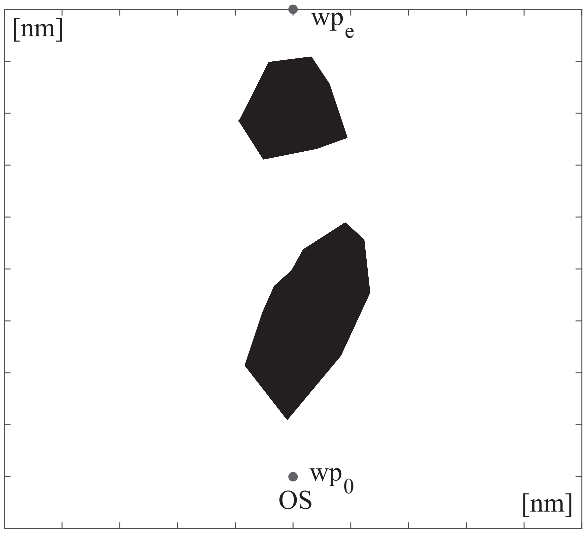

Fig. 6. Graphical presentation of test case 2 – OS at wp_0.

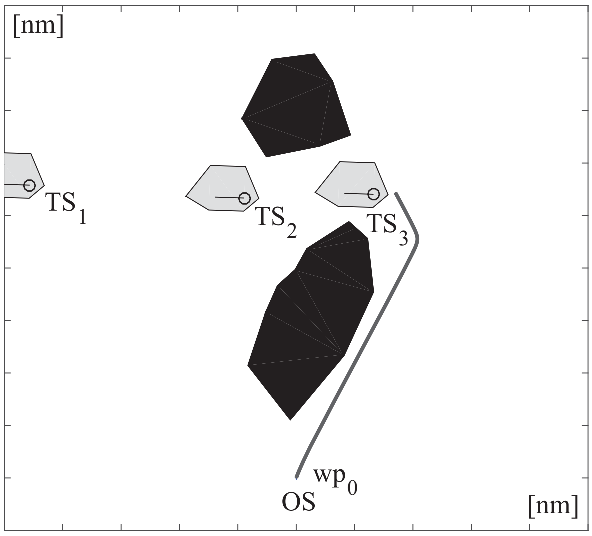

Fig. 7. Graphical presentation of test case 2 – OS moving along the trajectory.

TABLE III
RESULTS OF TEST CASE 1

path length (nm)	path fitness	course (deg)	computational time (s)
9.81	0.9714	22; 338	1.57

system (courses at consecutive parts of the trajectory) and the computational time. The OS trajectory constitutes a safe path. It allows the OS to avoid collisions with static and dynamic obstacles. It also fulfils the COLREGs, because the OS executes a manoeuvre to starboard as it is required (rules 14 and 15). The values of course alterations are also within the defined limits (more than 15 degrees and less than 60 degrees). The computational time for this test case was 1.57 seconds.

B. Test Case 2

TABLE IV
TEST CASE 2 MOTION PARAMETERS OF ALL SHIPS

Ship	Course (deg)	Speed (kn)	Bearing (deg)	Distance (nm)
OS	0	10	-	-
TS1	272	20	55	9
TS2	272	16	60	10
TS3	272	16	65	12

TABLE V
RESULTS OF TEST CASE 2

path length (nm)	path fitness	course (deg)	computational time (s)
9.92	0.95	25; 0; 335	2.28

This simulation scenario includes two static obstacles (islands) and three dynamic obstacles (TSs). The ship's motion parameters of test case 2 are given in Table IV. Figures 6 to 8 and Table V present results of test case 2. The solution of this test case also constitutes a safe path. The OS does not violate static and dynamic obstacles. The OS executes a manoeuvre to starboard according to rule 15 of COLREGs and the values of course alterations are within the demanded range (more than 15 degrees and less than 60 degrees). The computational time for test case 2 was 2.28 seconds.

V. DISCUSSION

The analysis of the achieved results can lead to the following remarks:

1. The method allows the calculation of a safe trajectory for the OS (a safe path for a moving object in a dynamic

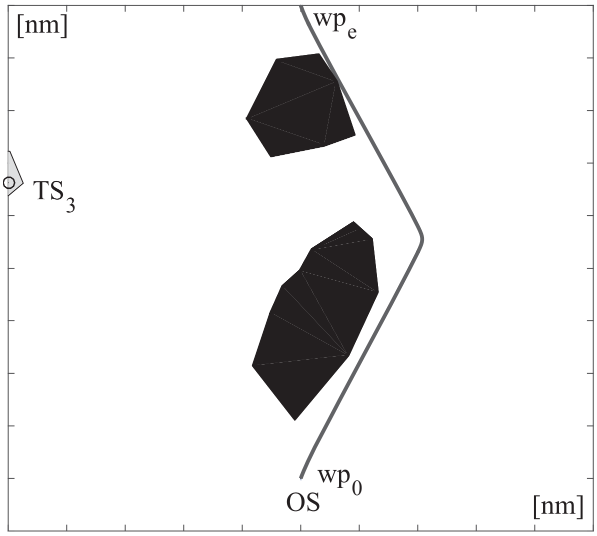

Fig. 8. Graphical presentation of test case 2 – OS at wp_e.

environment). The solution does not violate static and dynamic obstacles.

2. The solution returned by the algorithm fulfils the traffic code for ships (the COLREGs). The manoeuvres of the OS are executed to the proper side of the ship.
3. The course alterations along the calculated trajectory are in the predefined range (more than 15 degrees and less than 60 degrees), what ensures fulfilment of the rule 8b of COLREGs. Rule 8b specifies, that the manoeuvres have to be large enough to be readily apparent for other ships.
4. The computational time does not exceed a few seconds, what makes this approach applicable in commercial obstacle avoidance systems, which have to fulfil requirements of near-real time systems.
5. A multi-criteria fitness function allows taking into account all of the most important optimality criteria, such as path length, rules compliance, minimum and maximum values of course alterations. It enables achievement of a solution constituting a compromise between different criteria.
6. The presented approach enables consideration of the decision maker's (the system operator's) preferences, because he/she can define the criteria to be taken into account during problem solving.
7. The safety of solution is an essential condition. Due to that the evaluation of obstacles violation is not included in the fitness function, but is evaluated separately. Such approach guarantees achievement of a safe solution, if such exists.

VI. Conclusion

The paper presents a new, original approach applied to the problem of path planning for a moving object in a dynamic environment. The marine environment and the ship's path planning was chosen as a specific task, but the method can easily be generalised and applied to other environments and moving objects (mobile robots).

The method enhances the progress in the field of intelligent control systems and contributes to the development of autonomous systems. Application of the proposed algorithm enables the development of autonomous navigation, because the method is meeting the requirement of returning the solution in near-real time. The computational time for more complex situations does not exceed a few seconds.

Future works planned by the author include tests in real environment.

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