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Research article

Multi-objective path planning for unmanned surface vehicle with currents effects

Yong Ma [a,b], Mengqi Hu [c], Xinping Yan [d,*]

[a] School of Navigation, Wuhan University of Technology, 1178 Heping Road, Wuhan, Hubei, 430063, PR China
[b] Hubei Key Laboratory of Inland Shipping Technology, 1178 Heping Road, Wuhan, Hubei, 430063, PR China
[c] Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, Chicago, IL, 60607, United States
[d] National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, 1178 Heping Road, Wuhan, Hubei, 430063, PR China

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ABSTRACT

This paper investigates the path planning problem for unmanned surface vehicle (USV), wherein the goal is to find the shortest, smoothest, most economical and safest path in the presence of obstacles and currents, which is subject to the collision avoidance, motion boundaries and velocity constraints. We formulate this problem as a multi-objective nonlinear optimization problem with generous constraints. Then, we propose the dynamic augmented multi-objective particle swarm optimization algorithm to achieve the solution. With our approach, USV can select the ideal path from the Pareto optimal paths set. Numerical simulations verify the effectiveness of our formulated model and proposed algorithm.

1. Introduction

Featuring agile controllability, strong autonomy, and powerful field operational advantages, unmanned surface vehicles (USVs) have been extensively studied in the civil and military fields [1–4]. USVs are valuable for handling conventional maritime cruise and emergency rescue activities [5]. The paramount challenge that USVs face is the safety navigation [6], referring to the planning of high-quality conflict-free paths for such USVs. To guarantee the reasonable operation and quick response of reconnaissance and search missions, the path planning problem for USVs has become indispensable and ever-increasingly important.

Path planning for USVs is a branch of classical path finding for robots, including automatic ground vehicles (AGVs) and unmanned aerial vehicle (UAVs) [7] moving in the environment with obstacles. Different from the previous path finding for AGVs [8,9] and UAVs [10], generating an effective path for USVs is needed to optimally fulfill missions through the waters and satisfy generous constraints simultaneously. USV path planning is similar to the ship navigation problem reported in Refs. [11–13]. Ref. [11] planned the safest path for vessels to pass through mined waters. The velocity obstacles approach generates a cone-shaped obstacle in the velocity space and plans a near-optimal safe path for the USV [14]. The path with minimum travel time is achieved in Ref. [15], and the resultant path with minimum energy consumption is obtained in Refs. [16,17].

It is reasonable to identify that generous works depict the path planning problem as a single objective optimization model in which the objective can be to find the shortest path, the smoothest path, the most economical path (with minimum travel time or minimum energy consumption), the safest path, etc. Actually, the path length, smoothness, economic cost and safety goals play critical roles in USV path planning problems. It is necessary to pursue the shortest, smoothest, most economical and safest paths when the path planning issues are concerned. Quite sensibly, we focus on USV path planning studies with an emphasis on the above four objectives. Meanwhile, as noted in Ref. [15], owing to the drift generated by the currents and the inherent motion constraints of the underactuated USV [5,15,18], the effects of the currents [16–19] cannot be omitted in the USV path planning process. It is essential that currents effects should be concerned within the multi-objective USV path planning problems. Consequently, USV path planning studies with an emphasis on these four objectives, either explicitly or implicitly are reviewed in detail.

Obtaining the shortest path from the designed initial point to the final destination has been the main target of enormous quantities

* Corresponding author.
E-mail addresses: myongdl@whut.edu.cn (Y. Ma), mhu@uic.edu (M. Hu), xpyan@whut.edu.cn (X. Yan).

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of real-world engineering applications [20,21]. Extensive attention has been paid to the shortest path planning problem in the robotics field, including USVs, AGVs and UAVs. The studies strived to generate paths that were conflict-free, with the obstacles represented by certain shapes in a simplified environment [5]. Ref. [22] stated that the shortest path can be found with modified incremental heuristic algorithms. Ref. [23] formulated the global shortest path planning problem in a latticed environment as a single objective linear programming model and provided a novel label-correcting algorithm to study this model. Within the shortest path planning problems, the planning environment is oversimplified, and little attention has been paid to environmental effects.

By following a smooth path, a USV can avoid jerky motion and prolong the service life of its mechanical devices [22,24]. With a smooth path, the navigation, guidance and control of the USV can be substantially guaranteed [22,25]. In our previous studies [8,20,21], the optimal path was denoted by a highly smooth polynomial function and the path smoothness goal was realized automatically. An inadequacy of our previous work is that, owing to the lack of realistic maneuverability, the given paths are not applicable to engineering problems. During the navigation, guidance and control activities, the paths of the USV through the water are represented by line segments connected with a sequence of waypoints. It is critically necessary to choose the smoothest path for USV path planning problem. Meanwhile, formulation of the smoothest path goal should concern the practical usage of the USV.

The economical path of a USV can be evaluated in terms of travel time or energy consumption. With respect to long-term and high-energy-consumption voyages, time and energy savings become the foremost issues of the path planning problem. When engaging the activities, including transportation [26,27], cruise [28], and scientific investigation [29], the vessels would favor the most economical path, lowering the travel time and energy expenditure significantly. The resultant paths with minimum energy consumption are obtained in Refs. [16,17]. Refs. [16,17] verified that the energy consumption of the USV was markedly affected by the currents. Combined with the time cost function and the planning techniques, the sliding wavefront expansion approach analytically guarantees the feasible time-minimum path in strong currents [15]. Ref. [15] is the first attempt to introduce reinforcement learning for planning the minimum-travel-time path in ocean currents, whereas the obstacles and the motion boundary are not considered. To improve the practicability of the planned path, many constraints including the effects brought by currents [15], the obstacles, and the motion boundaries, should be incorporated into the path planning model. Reducing sailing time and energy consumption becomes remarkably essential when the USV needs to travel for a long journey affected by the currents.

Generally, the obstacles, including surface and underwater structures, impede the safety of USV navigation. Refs. [8,20,21] treated the obstacles as circles or spheres in two-dimensional or three-dimensional space, respectively, and safety was embedded as a constraint of the path planning problem. Ref. [30] provided the safest path planning for planar robots wherein an interval value was used to represent the safety. Owing to the absence of an intuitive safety representation, their work is hard to apply in practice to address path planning issues. Without the safety guarantee, a USV cannot successfully execute missions or tasks. To make up for the above deficiency and highlight the importance of safety, this work strives to optimize the path safety in the USV path planning problem.

From the above literature review, referring to the path planning problem for USVs in environments with currents effects, it can be observed that the formerly developed models aim to optimize only one single objective. The path length, path smoothness, economic cost and path safety are all important objectives in our focused issue. To the best of our knowledge, less attention has been paid to the joint optimization of the shortest, smoothest, most economical and safest goals in USV path planning problems that are subject to current effects, especially considering the above four objectives simultaneously. When comes to the complexity of our focused problems, the above four goals are generally conflicting criteria of the path planning problem, within which they interrelate with and restricting each other in the optimization process. To bridge these research gaps, we propose a multi-objective path planning algorithm for USVs by explicitly taking into account various constraints, especially the effects brought by currents.

Since the 1990s, generous fruitful works have been achieved in the domain of path planning, accompanied by promising algorithms [8,20,21]. The algorithms are classified as classical approaches and heuristic approaches [8]. With its rigid procedures, a classical approach can achieve an optimal solution if one exists, whereas a heuristic approach can obtain the solution when classical approaches lose effectiveness. Genetic algorithms [31], simulated annealing and evolutionary algorithm [8] belong to the heuristic approach category. The particle swarm optimization (PSO) algorithm [8,32–34] is subordinate to the heuristic approach and has the merits of simplicity, ease of implementation, and population-based evolutionary ability. Meanwhile, multi-objective PSO (MOPSO) algorithms have been developed for nearly two decades and have made considerable progress in tackling multi-objective optimization problems [35]. Ref. [30] adopted MOPSO to plan paths for robots and generated Pareto optimal paths. The fitness of MOPSO varies widely depending on the complexity and dimensionality of the considered problems [35]. The simultaneously optimized objectives are often reciprocally restrained. Taking the current influence into account, the shortest path of the USV may not correspond to the economical optimal path. The shorter path would be reached at the expense of the path safety used to endure the adversities brought by the current. Consequently, we propose a dynamic augmented MOPSO (DAMOPSO) to generate the high-quality Pareto optimal paths set for the USV wherein the multiple objectives and many constraints are embodied.

Some highlights of our paper are: (1) we consider multiple optimized objectives, including the travel length, the smoothness, the economic cost, and the safety of the path for USV path planning problem. Many constraints, such as the motion limitations and the currents effects are considered in our study; (2) we formulate a multi-objective optimization model for the USV path planning problem under environments with currents; (3) after analyzing the characteristics of the model, we introduce an algorithm DAMOPSO to conduct a trade-off analysis among the four objectives. Finally, simulations with different scenarios verify the effectiveness of the USV path planning model.

The remainder of the paper is organized as follows. Section 2 describes the USV path planning problem formulation. Section 3 analyzes the multi-objective model characteristics and proposes a solution approach DAMOPSO to resolve the problem. Section 4 presents illustrative numerical examples for USV path planning using the proposed approach. Finally, Section 5 concludes this paper.

2. Problem formulations

To expressly formulate the multi-objective path planning problem for unmanned surface vehicle with currents effects, this section presents the nomenclatures of the motion model and environment of the USV, our focused four objectives, and constraints. Following that, we sequentially illustrate the USV motion model, motion environment, and the multiple objectives of USV path planning in detail.