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The angle guidance path planning algorithms for unmanned surface vehicle formations by using the fast marching method

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ABSTRACT

By deploying multiple USVs as a formation fleet, benefits such as wide mission area, improved system autonomy and increased fault-tolerant resilience can be achieved. To efficiently and effectively navigate the USV formation, path planning algorithms are required to generate optimal trajectories and provide practical collision avoidance manoeuvres. In particular, as the USV is underactuated and is restricted by various motion constraints, this paper has presented a new algorithm named the 'angle-guidance fast marching square' (AFMS), to make the generated path compliant with vehicle's dynamics and orientation restrictions. Based upon the AFMS, a formation path planning algorithm has been proposed to guide the USVs safely navigating in a cluttered environment. In addition, the formation forming problem has been specifically investigated with the algorithm being developed to make the USVs capable of forming the desired shape by following the trajectories from random initial configurations (positions and orientations). In order to eliminate the potential collision risks occurring on the route, a novel priority scheme based upon the distance to the closest point of approaching (DCPA) has also been proposed and developed. Algorithms have been validated on the computer-based simulations and are proven to work effectively in different environments.

1. Introduction

With the advance of the autonomy technology as well as the drive of demand, there has been an increasing development of unmanned surface vehicles (USVs) in recent decade. The applications of USVs include military utilisations such as sea patrol [4] and coastal guarding [24], and civilian or scientific deployments such as environmental monitoring [34] and bathymetric survey [16]. However, as mentioned in Campbell et al. [5], most existing USV platforms are restricted by the problem of semi-autonomy, which prevents the USV from performing complex tasks requiring long endurance times. To overcome this, a promising strategy is to employ multiple USVs in formation fleet to allow cooperative operations. With sufficient monitoring and support amongst the vehicles, the USV formation would be able to exploit wide mission area, and have improved system robustness and increased fault-tolerant resilience [20].

A large number of studies have investigated the USV formation control, of which the primary aim is to design a series of low-level controllers for each vehicle's actuation system to maintain or track the desired positions and orientations relative to a defined reference point [35]. Favoured control strategies include the leader-follower control [6,30], the virtual structure approach [18,26] and the behaviour-based formation control [3,27]. By comparing and analysing the literature, it is found that not only can formation maintenance be achieved, but in some work high-level autonomous behaviour such as the collision avoidance can also be fulfilled by adding additional controllers [25,23].

However, the design of appropriate controllers, especially for USV formation, requires significantly more computational resources, which might not be an ideal option for the real-time navigation where fast response times are always needed [17]. An alternative to this is to solve the problem from the formation path planning perspective. Efficient path planning algorithms are capable of generating optimal way-points or paths within short time periods, and through employing simple trajectory controllers the formation performance can be enormously improved.

Hao and Agrawal [14] first proposed a formation path planning framework for unmanned ground vehicles in a dynamic environment by using the A* algorithm. Garrido et al. [12] and Gómez et al. [13] then employed this framework for mobile robots formation, and replaced the A* by the fast marching method (FMM) to generate better trajectories. Liu and Bucknall [20] improved these two works for USV formations application and specifically

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addressed the problem of collision avoidance with moving vessels in a practical maritime environment. However, there are two limitations associated with these researches, especially for the USV formation implementation. One limitation is the ignoring the vehicle's dynamics characteristics. The A* algorithm can only ensure the shortest path to be generated and requires additional path smoother to improve the features of the path to make it more feasible for a practical controller to follow. The FMM algorithm provides better performance in terms of the path smoothness and continuity than the A* does, however it sill does not fully address the dynamic constraints, especially without considering the vehicle's heading angles. The details of this problem will be explained further in the next section.

The second limitation when the algorithm being designed is the formation forming requirement, which is specially important for USVs. In the aforementioned works, the assumption has been made that the formation starts the mission with the desired shape already been formed. However, this is not a reasonable assumption as the USVs are normally launched offshore and are prone to drift caused by currents or waves, which makes it impractical to have the formation manually oriented in the correct shape and heading before the start of the mission. A more effective method is to make the USVs start from their random positions and move into the formation *en route*. Hence, it is worth breaking down the USV formation path planning into two separate stages, i.e. the formation forming and the formation path planning.

In this work a practical solution is offered to overcome these two limitations. A new angle guidance path planning algorithm based on the FMM, named angle-guidance fast marching square (AMFS), has been designed and developed specifically to make the generated path more compliant with the USV's dynamics. The AFMS is then used as the base algorithm for the USV formation path planning. Two individual algorithms are developed to solve the formation forming and formation path planning problems, respectively. By using the developed algorithms, the USV formation is better able to form the required shape safely and efficiently by following the generated trajectories. Some favourable formation behaviours such as the adaptive and flexible shape formation can be achieved to assure the navigation safety, which is the primary requirement in the maritime environment.

It also should be noted that while the formation shape is being formed, mutual collision of the USVs is an issue that needs to be addressed. Therefore, in this paper, a novel priority scheme based upon the distance to the closest point of approaching (DCPA) has been proposed to help with the elimination of the conflicts while the USVs are travelling. Compared with other priority algorithms such as the velocity based approach [19] and the environment based approach [7], the DCPA one is more suitable for marine applications as the DCPA is able to fast asses the collision risk and help to provide the most appropriate collision avoidance decisions [37].

The rest of the paper is organised as follows. Section 2 reviews the state-of-the-art algorithms in terms of the USV path planning. Section 3 specifically introduces the FMM algorithm as well as its improved version, the fast marching square (FMS) algorithm, which is able to increase the overall path safety. Section 4 describes the proposed AFMS method and compares it with the conventional FMM. Section 5 introduces the developed formation forming and formation path planning algorithms. The proposed algorithms and methods are verified by simulations in Section 6. Section 7 concludes the paper and discusses the future work.

2. Review of USV path planning algorithms

As regards USV path planning algorithm development, there has been a number of research methodologies. In the early stages, the evolutionary algorithm (EA) has been largely adopted to search for the feasible navigation route. Smierzchalski [36] first employed the genetic algorithm to generate an optimised route for marine vessel and developed a solution for collision avoidance with moving ships by adopting ship domain areas. A similar approach has also been used in Tam and Bucknall [38] but with special emphasise on generating practical evasive manoeuvres adhering to COLREGs.[1] Tsou and Hsueh [41] implemented the ant colony algorithm to design a decision-making system which can assist vessels navigating in the maritime environment and also obey the COLREGs. However, the major drawbacks of the EA are the inconsistency and incompleteness of the searching result, which hinders its adoption for practical purposes as the properties of the algorithm outputs cannot be guaranteed [39].

Hence, in recent years, the main effort has focused on using a deterministic search algorithm, such as the grid-based and artificial potential field (APF) methods, for USV path planning. Xue et al. [43] improved the APF to provide a safe collision free path in congested environments with multiple vessels to be avoided. Naeem et al. [28] designed a COLREGs compliant path planner by using a modified A* algorithm. A path trimmer was integrated into the A* algorithm to smooth the generated path making it more feasible for the vehicle to follow. Tam and Bucknall [39] proposed a cooperative path planning algorithm for USV with the main aim focusing on increasing the practicability and the completeness of the algorithm. Improved consistency and completeness can be seen through these algorithms to assure the same navigation path can be generated as long as the planning environment does not change. However, these works consider the path planning problem from the conventional perspectives, i.e. generating the path with the least distance cost while avoiding obstacles. It still needs to improve the path's quality, especially to make it compliant with USV's dynamics characteristics.

Kim et al. [15] proposed a novel angular rate constrained algorithm based on the *Theta**, which is a grid-based method similar to A*. The main concept behind this work is to redefine the feasible grid points in the planning space by referring to the turning rate of the USV, i.e. any points that are beyond the maximum turning range of the USV will be removed and not considered when generating the path. However, because additional functions were required in this algorithm, the overall computational time was increased, which takes more than double the time of the conventional *Theta**. In addition, because the algorithm still belongs to the grid-based method, the continuity of the path is highly dependant on the resolution of the planning space, which in turn affects the path's performance if a less rasterised space is used.

Recently, the fast marching method (FMM) based path planning algorithm becomes a new approach to generate smooth and continuous trajectory. The FMM shares the similar concept to the AFM of searching for the path based on the potential field. However, differing from the conventional way of combining all fields to generate the total potential field; the FMM produces the potential field by simulating the propagation of an electromagnetic wave, and the generated potential field does not suffer from the local minima problem, which is the main drawback of the APF [10].

The FMM calculates the path by using the gradient descent method over the potential field from the end point to the start point, and one of the most appealing features of the generated path is the guaranteed smoothness given that the generated potential field does not have any discontinuity [13]. No more path smoother is required to process the path, and the path can be easily executed

[1] COLREGs stands for The International Regulations for Preventing Collisions at Sea 1972, which should be followed by ships and other vessels at sea to prevent collisions between two or more vessels.