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A memetic algorithm for path planning of curvature-constrained UAVs performing surveillance of multiple ground targets

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Abstract The problem of generating optimal paths for curvature-constrained unmanned aerial vehicles (UAVs) performing surveillance of multiple ground targets is addressed in this paper. UAVs are modeled as Dubins vehicles so that the constraints of UAVs' minimal turning radius can be taken into account. In view of the effective surveillance range of the sensors equipped on UAVs, the problem is formulated as a Dubins traveling salesman problem with neighborhood (DTSPN). Considering its prohibitively high computational complexity, the Dubins paths in the sense of terminal heading relaxation are introduced to simplify the calculation of the Dubins distance, and a boundary-based encoding scheme is proposed to determine the visiting point of every target neighborhood. Then, an evolutionary algorithm is used to derive the optimal Dubins tour. To further enhance the quality of the solutions, a local search strategy based on approximate gradient is employed to improve the visiting points of target neighborhoods. Finally, by a minor modification to the individual encoding, the algorithm is easily extended to deal with other two more sophisticated DTSPN variants (multi-UAV scenario and multiple groups of targets scenario). The performance of the algorithm is demonstrated through comparative experiments with other two state-of-the-art DTSPN algorithms identified in literature. Numerical simulations exhibit that the algorithm proposed in this paper can find high-quality solutions to the DTSPN with lower computational cost and produce significantly improved performance over the other algorithms.

1. Introduction

Autonomous unmanned vehicles, e.g., unmanned aerial vehicles (UAVs), are increasingly being used in both civilian and military fields due to their low cost, high maneuverability, good survivability, and so on. Recently, there has been a growing interest in performing surveillance of multiple ground targets by UAVs. The primary goal of the path planning for UAVs is to fly

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through all the targets in the shortest time. To make the planned paths for UAVs flyable, the Dubins vehicle model is used to approximate the dynamics of UAVs where the constraints of UAVs' minimal turning radius can be taken into account. Meanwhile, due to the effective observation scope of the sensors equipped on UAVs, they only need to pass through one point within a certain neighborhood of each target. In this paper, we focus on finding the minimum-length curvature-constrained closed path through a collection of regions in a 2D plane.

1.1. Related work

The path planning problem for UAVs has been studied for decades.[1–5] In this paper, we are concerned with the optimal path planning problem of UAVs monitoring multiple ground targets. The well-known traveling salesman problem (TSP)[6] is aimed at determining the shortest path for a salesman to visit a series of cities, which measures the distance between any two cities by the Euclidean metric. In contract, the traveling salesman problem with neighborhood (TSPN)[7] takes targets as regions instead of points. An interesting application of the TSPN is the data mule robots[8–11] which are widely used in wireless sensor networks (WSNs) to collect data from WSN nodes. Usually, the total download time and the transmission ranges of the sensor nodes are the main factors to consider in the data mule problem. In this paper, to make the planned paths for UAVs flyable, the Dubins model (Eq. (1)) is used to describe the dynamic of UAVs with the constraints of minimal turning radius.

$$\begin{cases} \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta \\ \dot{\theta} = \dfrac{v}{r}u, u \in [-1, 1] \\ \dot{v} = 0 \end{cases} \tag{1}$$

where (x, y) and θ are the planar coordinates and the heading of the UAV, respectively, v is the speed of the UAV, r is the minimal turning radius, u is the control input, and a triplet (x, y, θ) is called as a configuration.

Dubins conducted some research on the model and drew conclusions on the shortest path between any two configurations. The shortest path from one configuration to another must be one of the six Dubins path patterns: RSL, LSR, RSR, LSL, RLR, and LRL,[12] where L means turning left with the minimal turning radius, R means turning right with the minimal turning radius, and S means moving along a straight line. From the conclusions, it can also be seen that the shortest Dubins path between two configurations relies on both their positions and their headings.

Many studies have been done on the Dubins traveling salesman problem (DTSP) which is another variant of the classic TSP for a Dubins vehicle. In contrast to the classic TSP, the Dubins distance between two points is used in the DTSP. It has been proved that the DTSP is NP-hard.[13] The existing methods to solve the DTSP can mainly be classified into two categories: decoupling methods and transformation methods. Decoupling methods determine visiting sequence and heading separately. Tang and Ozguner[14] determined the sequence by a heuristic method first, and then a gradient-based algorithm was used to optimize the heading of the UAV at the waypoints. Kenefic[15] determined the visiting sequence of waypoints by solving a corresponding Euclidean traveling salesman problem (ETSP), and then the particle swarm optimization (PSO) algorithm was used to optimize the heading of the UAV at these waypoints. Savla et al.[16] used the same method to determine the sequence and a method called alternating algorithm (AA) is used to construct the Dubins tour. The effectiveness of decoupling methods mainly relies on the similarity between the DTSP and its ETSP counterpart, which makes them unsuitable for the situations where the Euclidean distance between two points is not long enough as compared with the minimal turning radius of UAVs. Transformation methods[17–19] first sample the headings of waypoints, and then the DTSP is converted into an asymmetric traveling salesman problem (ATSP) by the noon-bean transformation which can be easily solved by some prevailing solvers, e.g., Lin-Kernighan heuristic LKH.[20] Transformation methods greatly depend on the sampling density of headings. To acquire a higher accuracy, they usually consume tremendous computational resources.

In real scenarios, considering the surveillance scope of the sensors equipped on a UAV, the UAV only needs to pass through a certain neighborhood of each target. The Dubins traveling salesman problem with neighborhood (DTSPN) is a more general variant of the DTSP which takes every target as a region. The literatures regarding the DTSPN are fairly limited. In contrast to the DTSP, the DTSPN is a more challenging problem. Obermeyer[21] used a genetic algorithm to solve the path planning problem for a UAV performing reconnaissance of static ground targets in terrain. Similarly, Guimaraes Macharet et al.[22] proposed a three-stage optimization process based on evolutionary algorithms to solve the DTSPN. Obermeyer et al.[23] proposed two sampling methods which extended the method used for the DTSP and transformed the problem into an ATSP. Isaacs et al.[24] developed a similar sampling method for scenarios with overlapped regions.

1.2. Main contributions

The main contributions of the paper are the following:

(1) Two approaches are proposed to predigest the solving difficulty of the DTSPN. Firstly, the Dubins paths in the sense of terminal heading relaxation are introduced, which makes the calculation of the Dubins distance easier. Secondly, based on the fact that a UAV must fly through the boundary of every target region, a boundary-based encoding scheme determining the visiting point of every target region is presented. These make the optimization scale of the DTSPN dropped from $4N$ to $2N$ (N is the number of targets), and the overall optimization difficulty is reduced dramatically.
(2) Based on the frame of memetic computing, a computationally efficient local search strategy based on approximate gradient with computational complexity $O(N)$ is developed. It can further improve the visiting point of each target region and enhance the quality of Dubins tours to a large extent. Meantime, a better tradeoff between exploration and exploitation in the solution space can be achieved by adjusting the executive strength of the local search strategy.
(3) The algorithm proposed for the DTSPN can be easily extended to deal with more complicated DTSPN variants with multiple UAVs and multiple groups of targets.