Journal of Electronics and Information Science (2023)
Clausius Scientific Press, Canada

DOI: 10.23977/jeis.2023.080508
ISSN 2371-9524 Vol. 8 Num. 5

Trajectory planning method for UAV inspection of transmission towers based on simulated annealing algorithm

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Keywords: Unmanned Aerial Vehicles, Trajectory Planning, Simulated Annealing Algorithm

Abstract: Efficiently planning the trajectory of unmanned aerial vehicles (UAVs) for power grid inspections is a critical factor in ensuring the performance of such inspections and represents a current research hotspot in the field of UAV-based power grid inspections. In this study, addressing the limitations of traditional algorithms in meeting the requirements of UAV inspections, we propose a multi-objective Traveling Salesman Problem (TSP) optimization model. This model aims to optimize the UAV trajectory while considering both speed and prioritizing visits to towers with multiple defects. The simulated annealing algorithm is employed to solve this optimization problem and implement it through MATLAB programming. The results show that the path distance obtained after applying the algorithm converges more effectively towards the optimal solution. This demonstrates the effectiveness of the proposed algorithm in addressing the optimization challenges related to UAV-based inspection trajectories.

1. Introduction

In China, the traditional method of power grid inspection relies on manual labor, which employs rather limited means. It primarily relies on handheld lightweight maintenance tools and visual inspection through binoculars to identify defects. This approach falls short in providing a detailed and comprehensive understanding of the overall condition of transmission towers, particularly in the high-altitude blind spots at the top of these towers [1]. With a multitude of transmission lines of varying specifications scattered across complex and intertwined terrains, such as mountains, hills, and other challenging landscapes, power line inspections have become exceedingly difficult and dangerous, while also consuming significant manpower and resources [2].

As the times have evolved and with the rapid advancements in aerospace technology and scientific innovations, the application of unmanned aerial vehicles (UAVs) has made significant breakthroughs in the field of power grid inspections. Researchers like Wang Bo from Dalian University of Technology [3] have utilized multi-rotor UAVs as platforms to construct UAV-based power grid inspection systems with autonomous flight control capabilities and defect detection capabilities. Similarly, Chen Wenhao from Zhengzhou University [4] has worked on improving GPS accuracy and eliminating barometric pressure sensor noise to design autonomous power line inspection processes for quadcopter UAVs. UAV trajectory planning involves designing the motion strategy of UAVs (including environmental and self-constraints) to generate an optimal path between the starting point and the target point while avoiding obstacles in the flight environment. Effective trajectory planning allows UAVs to promptly identify and mitigate safety hazards in power line inspections, enhance inspection efficiency, and extend the inspection range and intensity [5]. Therefore, researching algorithms for UAV-based power line inspection trajectory planning holds significant theoretical and practical significance.

Although scholars both domestically and internationally have conducted extensive research on unmanned aerial vehicles (UAVs) for power grid inspections and have achieved certain research outcomes, their focus has primarily centered on aspects such as UAV electromagnetic field obstacle avoidance strategies, transmission line fault detection, and the determination of safe flight areas for UAVs. In the domain of UAV path optimization, numerous algorithms have been explored, with examples including the Dijkstra algorithm and the particle swarm algorithm, which represent mathematical methods employed for addressing such problems. The traditional Dijkstra algorithm is a single-source shortest path algorithm based on breadth-first search. However, this algorithm consumes a significant amount of time calculating irrelevant data and is unable to determine all the shortest paths from one vertex to all other vertices [6]. On the other hand, the particle swarm algorithm belongs to the category of swarm intelligence algorithms and draws inspiration from the behavior of bird flocks. Nevertheless, during the optimization process, the performance of the particle swarm algorithm is constrained by both the complexity of the problem itself and the tendency to converge to local optima [7].

The simulated annealing algorithm is a stochastic search-based optimization algorithm, inspired by the process of annealing metals, where a solid is heated to a high temperature and then slowly cooled to improve its toughness (ability to bend). Its underlying principle lies in the fact that during the cooling phase, the grains within the solid can rearrange themselves with lower energy, and the simulated annealing algorithm simulates this post-heating annealing process. The objective of this algorithm is to find the global optimal solution or a solution that approximates the optimal one within the solution space. Compared to the particle swarm algorithm and the Dijkstra algorithm, the simulated annealing algorithm can avoid getting stuck in local optima within the solution space, and it possesses robust global search capabilities, making it suitable for solving large-scale and complex problems. At Northwest A&F University, Fan Yeman [8] employed this algorithm to propose a UAV mountainous operation path planning method based on energy consumption optimization. This study demonstrates that the simulated annealing algorithm can be used to plan the optimal energy-efficient path for UAV operations under energy constraints, yielding favorable planning results. Li Rong [9] conducted research on UAV flight control law assessment techniques based on the simulated annealing algorithm, addressing the worst-case search problem within control quality specification criteria, thereby achieving effective evaluation. Wang Qiang from Northwestern Polytechnical University [10] established an improved artificial potential field model and used the simulated annealing algorithm to plan feasible trajectories for Unmanned Combat Aerial Vehicles (UCAVs). Wang Yi, also from Northwestern Polytechnical University [11], developed a UAV path planning algorithm based on the PH curve and utilized the simulated annealing algorithm to generate flyable paths that satisfy UAV kinematic constraints.

Considering the aforementioned research developments, this paper incorporates real-distance factors and establishes a multi-objective TSP optimization model. The objective is to ensure speed and prioritize visits to towers with multiple defects. The simulated annealing algorithm is then employed to solve this optimization problem, aiming to optimize the trajectory of UAV inspections for transmission towers. This research provides algorithmic support for defect detection in UAV-based power line inspections."

2. Proposed method

2.1 The establishment of model

To optimize the inspection trajectory for UAV-based power line inspections of transmission towers, the following method can be devised for planning the inspection route. Firstly, all transmission towers within the inspection area are ranked based on the severity of potential defects. Subsequently, the UAV takes off from the operations center and selects the tower with the most severe defect as the priority tower for inspection. Furthermore, a balance is struck between the severity of defects and the distance traveled, considering the weightings of these factors on UAV inspection efficiency. The UAV proceeds to the next tower with either more severe defects or a shorter path until all towers have been inspected. Finally, the UAV returns to the operations center, completing the entire inspection task. The UAV Inspection Workflow Diagram is shown in Figure 1. Through this approach, we can effectively plan the flight path, prioritize the handling of severe issues, and maximize inspection efficiency and coverage area, ensuring that each transmission tower is thoroughly inspected.

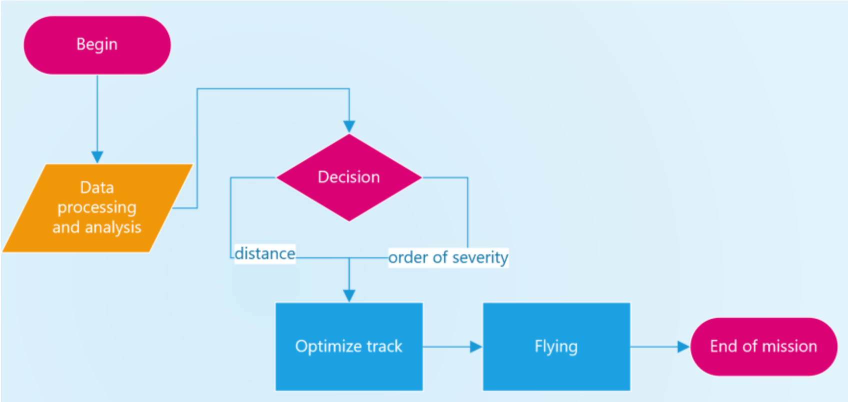

Figure 1: UAV inspection workflow diagram

2.2 Establishment of a trajectory optimization model

The Traveling Salesman Problem (TSP) is a classic NP-combinatorial optimization problem that is widely applied in various fields, such as integrated circuits and logistics distribution. In order to enable an unmanned aerial vehicle to inspect all transmission towers in the shortest possible time, the pending inspection towers can be considered as nodes to be visited, and the power lines between two electrical towers are abstracted as line segments with arbitrary directions, ensuring that each tower is visited in a single operation to accomplish the inspection task for all towers along that route within the region.

This study can be summarized as a TSP problem, where an unmanned aerial vehicle takes off from the maintenance center and passes through n transmission tower nodes. To avoid redundant visits and detours during inspection, the path is constrained so that each node can only be visited once. Taking into account the actual conditions, the severity of defects and vulnerabilities in each tower varies, and priority is given to inspecting and rectifying the towers with more severe issues. The objective optimization function in this paper is defined based on the fact that the energy consumption and time of the unmanned aerial vehicle are usually directly proportional to the flight distance:

$$\min f(x) = \sum d_{ij} x_{ij} \quad (1)$$

$$s.t.\begin{cases} \sum_{j=1}^{n} x_{ij} = 1, i = 1,2,3\cdots n \\ \sum_{i=1}^{n} x_{ij} = 1, j = 1,2,3\cdots n \\ \sum_{i,j\in s} x_{ij} \le |s| - 1, 2 \le |s| \le n-1, s \in \{1,2,\cdots n\} \\ x_{ij} \in \{0,1\}, i,j = 1,2,\cdots n, i \ne j \end{cases} \quad (2)$$

where, d_{ij} represents the distance between tower i and tower j, and x_{ij} = 0 or 1 (1 indicates passing through both tower i and j, 0 indicates not passing through both tower i and j), and the optimal values of the objective function are successively determined.

3. Results

Selecting 25 transmission towers in a certain plain area and simulating the quantity of defects. For the sake of computational convenience, relative coordinates are assigned to each tower, as shown in Table 1.

Table 1: The relative coordinates and the quantity of defects for each transmission tower

Number	Number of Defect Quantity	Coordinates	Number	Number of Defect Quantity	Coordinates
1	4	(113.0,43.0)	2	5	(18.0,49.0)
3	10	(48.0,15.0)	4	3	(75.0,34.0)
5	4	(28.0,4.0)	6	6	(3.0,34.0)
7	6	(102.0,0.0)	8	7	(64.0,12.0)
9	5	(104.0,23.0)	10	7	(71.0,20.0)
11	10	(104.0,46.0)	12	10	(18.0,28.0)
13	5	(80.0,41.0)	14	7	(53.0,44.0)
15	6	(21.0,30.0)	16	3	(95.0,48.0)
17	4	(49.0,13.0)	18	7	(113.0,27.0)
19	1	(108.0,0.0)	20	3	(41.0,48.0)
21	3	(63.0,18.0)	22	1	(96.0,34.0)
23	2	(23.0,29.0)	24	5	(106.0,55.0)
25	2	(82.0,55.0)			

Since this project involves an NP combinatorial optimization problem, we employed MATLAB 2022a for programming and solving. The parameter settings include a cooling rate 'k' with a value of 0.99, an initial temperature 'T0' of 2500 degrees, a final temperature 'Tend' of 0.001, and a chain length 'L' set to 100. These settings were applied to the optimization and solving processes while satisfying Equation 2. After 132 iterations, the calculated optimal distribution path is as follows:

Starting coordinates: 80 41; Coordinates of the final point: 82 55; Optimized shortest distance: 365.1164. The visualized simulation results are shown in Figure 2 and Figure 3.

It is evident that the fitness gradually stabilizes towards the optimal solution throughout the annealing process, indicating the algorithm’s convergence. Following the algorithm's steps for computation, the total delivery distance is calculated to be 365.164 kilometers.

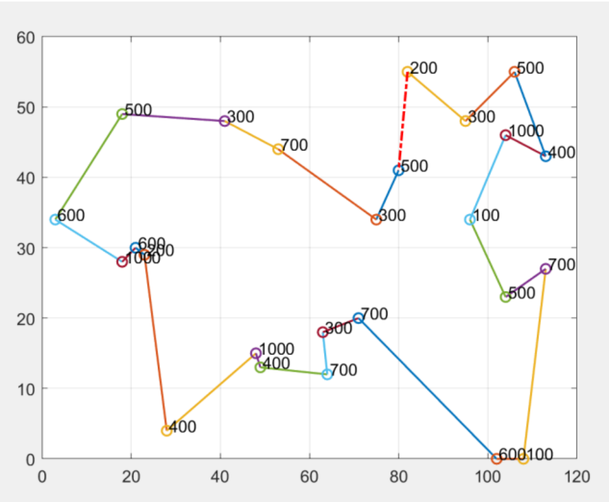

Figure 2: The visualized simulation results of planned trajectory

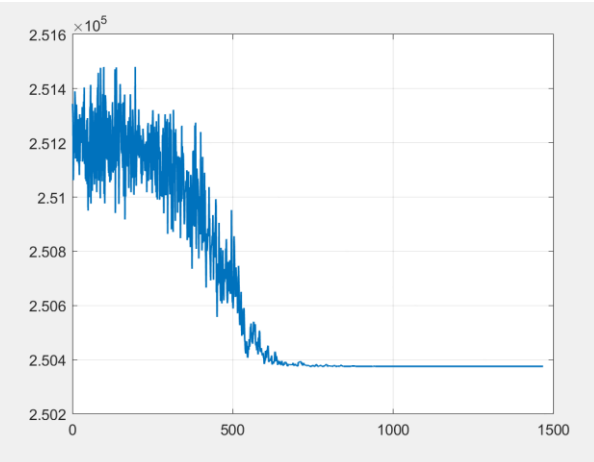

Figure 3: The visualized simulation results of optimization

4. Conclusions

This paper addresses the current challenge of traditional algorithms not meeting the requirements of drone inspections. A multi-objective TSP optimization model that ensures speed and prioritizes visiting towers with more defects is established. The simulated annealing algorithm is employed for solving the problem and implement it using MATLAB. After applying the algorithm, the path distance converges more effectively towards the optimal solution, demonstrating the effectiveness of this algorithm in solving the drone inspection trajectory optimization problem. However, in the application of power inspection, other constraints of UAV trajectory planning, such as path length and number of turns, have an important impact on the operation efficiency of UAV. These constraints are the focus of future improvement of the proposed algorithm.

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