

Path Planning Method for UAV in Complex Mountainous Areas Based on Meta-heuristic Algorithms

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Abstract: In recent years, drone technology has been rapidly advancing, and its application areas are continuously expanding. In disaster response and search and rescue operations, drones can access areas that are difficult or unsafe for humans to reach. Path planning for drones in complex mountainous environments has always been a crucial component of drone technology. Metaheuristic algorithms, compared to traditional algorithms, exhibit excellent flexibility and diversity in this field, and have become an effective means of solving complex multi-constraint combinatorial optimization problems due to their speed and efficiency. This paper conducts comparative experimental tests on the latest eight metaheuristic drone path planning algorithms, verifying their effectiveness in complex environments and revealing the characteristics and advantages of each algorithm. RBMO demonstrates the most superior performance and stability in complex mountainous environments. On the other hand, the SSA algorithm exhibits the fastest convergence speed. This paper provides a theoretical reference for research on drone path planning problems.

Keywords: UAV, Path Planning, Meta-heuristic Algorithms, Complex Mountainous Environments.

1. Introduction

Unmanned aerial vehicles (UAVs), commonly known as drones, are aircraft that can be remotely controlled or operate autonomously. They are used in various fields like military reconnaissance, aerial photography, agriculture, and logistics. UAVs are equipped with advanced sensors and cameras, enabling them to capture high-definition images and videos, and achieve precise positioning and flight. With technology advancements, drones have become increasingly intelligent, capable of executing complex tasks. Their lightweight design and user-friendly operation make them an indispensable tool in modern technology.

With the continuous development of drone technology and the expanding application scenarios, path planning for drones has become a critical issue in the field of drone applications, holding significant importance for autonomous flight and mission execution. Advanced path planning algorithms can ensure the global optimality of the flight path, dynamically avoid obstacles in real-time, and enhance the overall flight efficiency of drones.

Researchers from both academia and industry have conducted extensive and in-depth studies on UAV path planning. Classical UAV path planning algorithms [1] can be primarily categorized into three types. Graph-based path planning algorithms, such as A* and Dijkstra, convert the drone

environment into a graph and use search algorithms to find the best path, but their precision is limited by the search space size. Sampling-based algorithms, like PRM and RRT, generate an optimal path by sampling points in the free space, but their accuracy depends on sampling density. The artificial potential field algorithm creates a virtual field in the environment, treating obstacles as repulsive forces and the target as attractive, simulating the motion of charged particles to avoid obstacles and find the shortest path. While efficient, its effectiveness is limited by the potential field's characteristics, often resulting in local optima.

Meta-heuristic algorithms [2], also known as intelligent bionic algorithms, have been widely studied in recent years as a method for UAV path planning. These algorithms utilize artificial intelligence techniques, such as neural networks, genetic algorithms, particle swarm optimization, ant colony optimization, wolf pack algorithms, and bee colony algorithms, to search for optimal paths. These algorithms exhibit a certain degree of robustness and adaptability, making them more suitable than traditional algorithms for solving optimal path problems in complex mountainous environments.

This paper focuses on eight typical meta-heuristic algorithms proposed in the industry over the past five years, conducting experimental comparative analyses of their path planning capabilities in complex mountainous environments, thereby providing a reference for research on flight path planning algorithms in the UAV field. The structure is organized as follows: Section 2 introduces the research work and literature review in the relevant field. Section 3 presents the Design of Objective Functions for UAV Path Planning in Complex Mountainous Environments. Section 4 presents and evaluates the experimental results. Finally, Section 5 concludes the paper and points out further work.

2. Related work

The SSA algorithm proposed by Xue, J. K. and Shen, B. [3] is renowned for its novelty and rapid convergence speed, enabling it to effectively identify global optimal solutions. This characteristic of fast convergence allows SSA to swiftly plan reasonable flight paths for UAV in path planning scenarios. Hashim, F. A. and Hussien, A. G. [4] proposed the SO algorithm in 2022, which simulates the predatory behavior of snake groups in nature. This algorithm is renowned for its rapid convergence speed, allowing it to find satisfactory solutions within a relatively small number of iterations. This feature is particularly crucial for real-time UAV path planning, where timely and effective solutions are essential. The RIME algorithm proposed by Su, H. et al. [5] effectively explores the search space by simulating the random motion of ice crystals, thereby avoiding local optima. In the context of UAV path planning tasks, even when faced with different environments and mission requirements, the RIME algorithm can quickly adapt and provide effective solutions. Trojovský, P. and Dehghani, M. [6] proposed the SABO algorithm, which updates the positions of population members in the search space by simulating the subtraction average of search agents. It gradually converges to the optimal solution over multiple iterations, demonstrating strong global search capabilities. The SAO [7] algorithm draws inspiration from the natural process of snow melting, simulating the melting path of snow over complex terrains to identify the optimal path for unmanned aerial vehicles (UAVs) in intricate mountainous environments. The SAO algorithm and its improved versions [8] have demonstrated several advantages in UAV path planning, including the simulation of natural processes, global optimization capabilities, adaptability to complex environments, dynamic adjustment abilities, and superior performance of the enhanced algorithm. Abdel-Basset, M. et al. [9] proposed a meta-heuristic algorithm inspired by the defensive behavior of porcupines, which exhibits robust global and local search capabilities. The CPO algorithm is capable of adapting to the complex urban terrain for three-dimensional trajectory planning of unmanned aerial vehicles (UAVs), effectively generating obstacle-avoidance-compliant 3D UAV trajectories with high planning efficiency. The Red-billed Blue Magpie Optimizer (RBMO) was proposed by Fu Shengwei et al. [10] in 2024, inspired by the efficient cooperative foraging behavior of the red-billed

blue magpie. The RBMO algorithm demonstrates competitiveness in solving multi-objective optimization and constrained optimization problems, particularly showcasing potential in applications such as multi-UAV cooperative path planning. The Secretary Bird Optimization Algorithm (SBOA) [11] is a novel metaheuristic algorithm inspired by the survival capabilities of secretary birds to address real-world optimization problems. Compared to traditional path planning algorithms, the SBOA demonstrates superior performance in three-dimensional path planning for multi-UAV cooperative swarm obstacle avoidance.

3. Flight path planning methods

Flight path planning is a comprehensive process that requires the integration of multiple factors, including safety, efficiency, reliability, real-time performance, cost-effectiveness, regulatory compliance, mission requirements, environmental adaptability, communication, multi-UAV coordination, precision, and user-defined constraints, to ensure that unmanned aerial vehicles (UAVs) can complete tasks safely and efficiently.

3.1. Flight challenges in complex mountainous terrain

Mountainous terrain, with its rugged topography and varying elevations, presents challenges for unmanned aerial vehicle (UAV) flight path planning. UAVs need to navigate around obstacles, which can increase flight distance and time. Traditional path planning algorithms are inefficient and may fail to identify feasible paths in complex mountainous environments. The environment presents challenges for UAVs including safety, path planning, flight efficiency, communication stability, and sensor navigation. The operation of UAVs imposes higher demands on path planning algorithms.

3.2. Objective function design

In UAV path planning, the objective function serves as a critical component for evaluating and optimizing path performance. It is typically a mathematical expression used to quantify certain characteristics of the path, thereby guiding the process of searching for the optimal path.

3.2.1. Flight length

The length of the flight path is a crucial criterion for evaluating path quality. A shorter path length is more conducive to energy conservation and efficiency improvement for UAV. The calculation of the flight path length is shown in Equation (1).

$$F_1(x_i) = \sum_{i=1}^n \text{sqrt}((x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2) \quad (1)$$

n represents the number of flight trajectory points, and x, y, z represents the 3D coordinates of the waypoint.

3.2.2. Flight altitude

The flight altitude of unmanned aerial vehicles (UAVs) is crucial not only for flight safety but also directly impacts the quality of aerial photography and the scope of observation. Generally, the flight altitude of UAVs needs to be controlled within a specific range. The calculation of flight altitude is shown in Equation (2-3).

$$H_{ij} = \begin{cases} \left| h_{ij} - \frac{(h_{\max} - h_{\min})}{2} \right|, & \text{if } h_{\min} \leq h_{ij} \leq h_{\max} \\ \infty & \text{otherwise} \end{cases} \quad (2)$$

$$F_2(x_i) = \sum_{j=1}^n H_{ij} \quad (3)$$

When the flight altitude exceeds the specified range, corrective penalties will be imposed.

3.2.3. Flight smoothness

The path planning of unmanned aerial vehicles (UAVs) should minimize large-angle yaw and sudden changes in altitude, ensuring the path remains smooth. Due to the steep and highly varied terrain in mountainous areas, the flight path of UAVs must meet the requirements of the maximum climb angle and climb rate. The smoothness function is shown in Equation (4-6).

$$\varphi_i = \arctan \left(\frac{\|l_i l_{i+1}\|}{l_i l_{i+1}} \right) \quad (4)$$

$$\phi_i = \arctan \left(\frac{z_{i+1} - z_i}{\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}} \right) \quad (5)$$

$$F_3(x_i) = a_1 \sum_{j=1}^{n-2} \varphi_{ij} + a_2 \sum_{j=1}^{n-1} |\phi_{ij} - \phi_{i,j-1}| \quad (6)$$

l_i represents the distance between two waypoints, ψ_i denotes the horizontal turning angle, φ_i represents the vertical pitch angle, and a_1 and a_2 are penalty coefficients.

3.2.4. Flight obstacles

During flight in mountainous environments, UAV need to navigate around numerous obstacles without collisions. K represents the set of all obstacles, D denotes the diameter of the UAV, S represents the safe distance between the UAV and the collision domain, and d_k denotes the straight-line distance from the UAV's flight path to the center of an obstacle. For the set of obstacles K , the mathematical model of the safety cost function for the UAV traveling from node P_{ij} to node $P_{i,j+1}$ is given by Equation (7-8).

$$F_4(X_i) = \sum_{j=1}^{n-1} \sum_{K=1}^K T_k(P_{ij} P_{i,j+1}) \quad (7)$$

$$T_k(P_{ij} P_{i,j+1}) = \begin{cases} 0, & \text{if } d_k > S + D + R_k \\ (S + D + R_k) - d_k, & \text{if } D + R_k < d_k \leq S + D + R_k \\ \infty, & \text{if } d_k \leq D + R_k \end{cases} \quad (8)$$

3.2.5. Objective function

The problem of UAV path planning can be simplified into a polyline planning problem. Taking into account the operational requirements of the UAV, the objective function for UAV path planning is constructed by calculating the flight length cost, flight altitude cost, smoothness cost, and obstacle avoidance cost, as shown in Equation (9).

$$F(x_i) = \sum_{k=1}^4 b_k F_k(x_i) \quad (9)$$

x_i is the decision variable, b_k represents the weight of each cost function, and F_k denotes the cost function.

4. Experiment and evaluation

The experiment utilized the MATLAB platform to simulate a 3D model of a complex mountainous environment. Within the 3D model, restricted area (RA) were designated. Under the same mountainous model, eight path planning algorithms (RIMA, SABO, SO, CPO, SAO, SSA, RBMO, SBOA) were tested using identical starting point (SP) and endpoint (EP).

4.1. Experimental test results

The results of UAV path planning are shown in Figure 1, and the convergence curves of the objective functions for eight UAV path planning algorithms are illustrated in Figure 2.

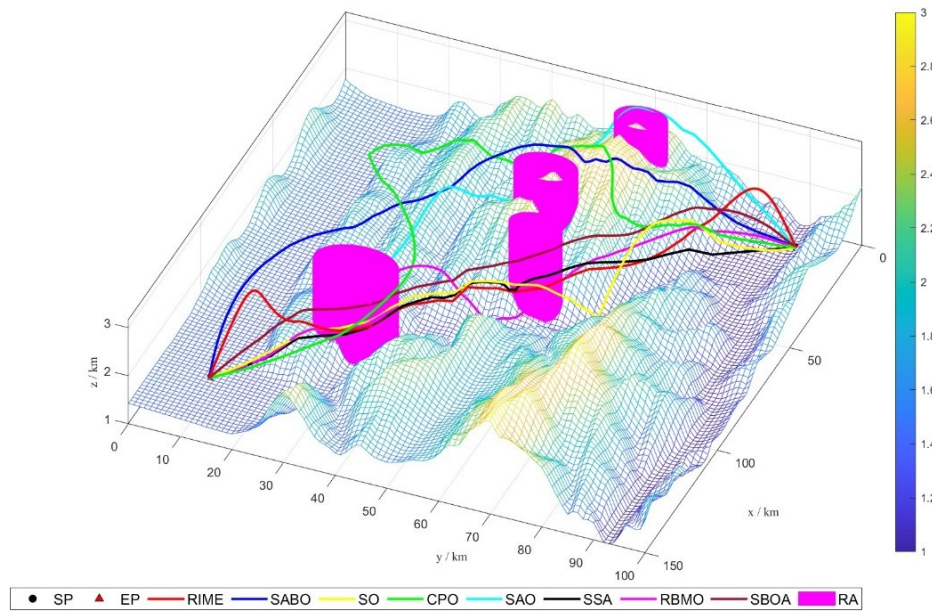


Figure 1: Experimental results of metaheuristic algorithms for UAV path planning

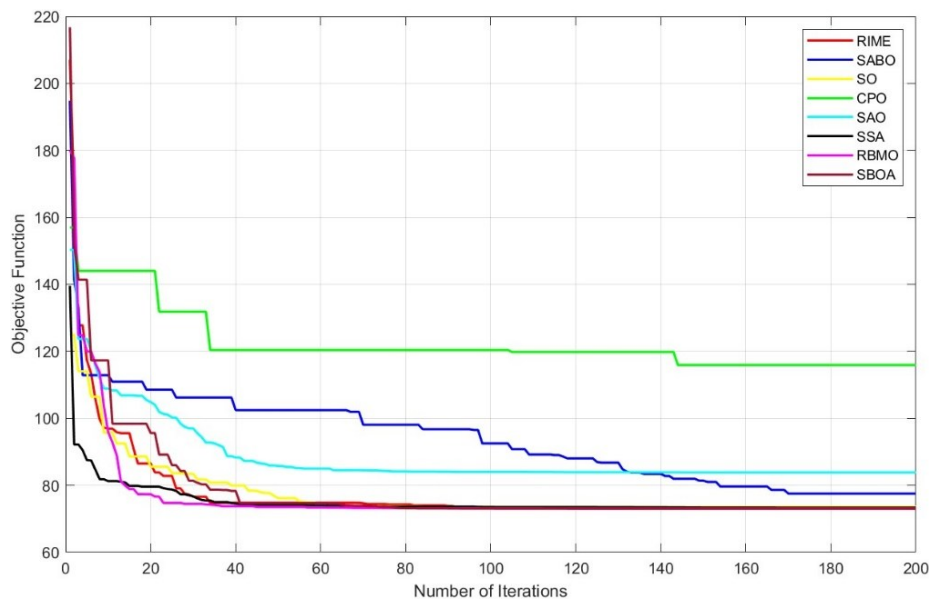


Figure 2: Metaheuristic algorithms objective function curve

The experimental results indicate that metaheuristic algorithms exhibit varying performance in completing UAV path planning tasks in complex geological disaster scenarios. In mountainous environments with significant elevation changes, the convergence speed of their objective functions also differs. Under the same conditions, we repeated the experiment 30 times, and the statistical analysis of the experimental data is presented in Table 1.

Table 1: Metaheuristic algorithms experimental data

Algorithms	RIME	SABO	SO	CPO	SAO	SSA	RBMO	SBOA
Objective Function	73.26	86.26	73.51	110.99	80.98	73.24	73.03	73.65
Standard Deviation	0.21	26.46	0.91	9.13	7.16	0.14	0.06	2.54

4.2. Discussion

Through comparative experiments, it can be observed that the five algorithms, namely RIME, SO, SSA, RBMO, and SBOA, all exhibit commendable path planning capabilities. Among the tested algorithms, RBMO demonstrates the most superior performance and stability in complex mountainous environments. The SSA algorithm, on the other hand, exhibits the fastest convergence speed.

5. Conclusion

This paper constructs an experimental platform to simulate complex mountainous environments and conducts comparative tests on eight meta-heuristic UAV path planning algorithms proposed by researchers in recent years. The experimental results demonstrate the distinct characteristics and applicability of each algorithm. This study provides a theoretical reference for further exploration of UAV path planning solutions in complex mountainous environments in the future.

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