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An improved constrained differential evolution algorithm for unmanned aerial vehicle global route planning

Xiangyin Zhang [a,b], Haibin Duan [a,b,*]

[a] State Key Laboratory of Virtual Reality Technology and Systems, Beihang University (BUAA), Beijing 100191, PR China
[b] Science and Technology on Aircraft Control Laboratory, School of Automation Science and Electrical Engineering, Beihang University (BUAA), Beijing 100191, PR China

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ABSTRACT

This paper formulates the global route planning problem for the unmanned aerial vehicles (UAVs) as a constrained optimization problem in the three-dimensional environment and proposes an improved constrained differential evolution (DE) algorithm to generate an optimal feasible route. The flight route is designed to have a short length and a low flight altitude. The multiple constraints based on the realistic scenarios are taken into account, including maximum turning angle, maximum climbing/gliding slope, terrain, forbidden flying areas, map and threat area constraints. The proposed DE-based route planning algorithm combines the standard DE with the level comparison method and an improved strategy is proposed to control the satisfactory level. To show the high performance of the proposed method, we compare the proposed algorithm with six existing constrained optimization algorithms and five penalty function based methods. Numerical experiments in two test cases are carried out. Our proposed algorithm demonstrates a good performance in terms of the solution quality, robustness, and the constraint-handling ability.

1. Introduction

Unmanned aerial vehicles (UAVs) can greatly increase the capability of high-risk targets penetration, suppressing enemy air defense, deep target attacking and dominating the battle space. Route planning and optimization is one of the most important problems in the autonomous navigation process of UAVs [1,2]. It allows the UAV to autonomously compute the best path from a start point to an end point [3]. For both the civil and military tasks of the UAV, the route planning is often formulated as an optimization problem, where the feasibility of the candidate route depends on the mission, environment and UAV physical constraints. Meanwhile, the optimality of the candidate route is evaluated according to the planning criteria, such as minimal path length or destruction risk [4]. Previous research has proposed series of algorithms to solve the UAV route planning problem, for example, the graph-based methods, such as the Voronoi diagram search method [5]; the grid-based methods, such as the mathematical programming methods, the A* searching algorithm [6] and the bi-level programming based method [7]; the nature inspired methods, such as the artificial physics algorithm [8] and the evolutionary computation technique [9–11]; and other methods, such as optimal control based methods [12] and sampling based methods.

The global and integrative optimization of the flight route is important content of the modern flight vehicle design, which can be in favor of improving flight qualities to meet the technical requirements for all determined missions [13]. It has been proven that finding the optimal route is an NP-hard problem, and the problem complexity increases very quickly as the size of the problem grows. To reduce the complexity, many researchers have applied the population-based algorithms to solve the route planning problem, including genetic algorithm (GA) [3–5], particle swarm optimization (PSO) [14,15], ant colony optimization (ACO) [16–18], artificial bee colony (ABC) [19], differential evolution (DE) [20–22], gravitational search algorithm (GSA) [23], intelligent water drops optimization (IWD) [24], and memetic computing method [25]. Zheng et al. [9] adopted the evolutionary computation to design a real-time route planner for UAV. Besada-Portas et al. [4,10] presented a UAV path planner based on evolutionary algorithms for realistic scenarios. The planner can return the paths that fulfill and optimize the multiple criteria, with the properties of real UAVs, terrains, radars, and missiles taken into consideration.

* Corresponding author at: Science and Technology on Aircraft Control Laboratory, School of Automation Science and Electrical Engineering, Beihang University (BUAA), Beijing 100191, PR China. Tel.: +86 10 82317318.
E-mail address: hbduan@buaa.edu.cn (H. Duan).

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Roberge et al. [3] compared the performance of GA and PSO in computing feasible and quasi-optimal paths for fixed wing UAVs in a complex 3D environment, and a multiobjective cost function is developed to evaluate the characteristics of the optimal path. Moreover, by using a parallel implementation on standard multicore CPUs, they drew the conclusion that real-time path planning for UAVs is possible. Fu et al. [14] proposed the phase angle-encoded and quantum-behaved particle swarm optimization (θ-QPSO) to generate a safe and flyable path for the UAV in the presence of different threat environments.

Recently, differential evolution (DE) [26] has been successfully applied in many research and application areas. The recent two reviews on DE can be seen in [27] and [28]. Compared with many other population-based algorithms, DE is much simpler and straightforward to implement, which only takes several lines to code the core part of the algorithm in any programming language [28]. Despite its simplicity, DE exhibits the outstanding performance on a wide variety of problems including unimodal, multimodal, separable, non-separable and so on, and many modified versions of DE has been proposed for both unconstrained and constrained optimization problems [27–29]. Several existing researches have studied the application of the DE to the UAV route planning problem. Brintaki et al. [20] adopted the DE algorithm to design a 2D offline path planner for multi-UAVs coordinated navigation in known static maritime environments. Zhou et al. [21] presented a three-dimensional (3-D) trajectory planning algorithm for UAV based on an improved DE algorithm. Moreover, considering that the route planning problem is truly a multi-objective optimization problem in which conflicting goals of minimizing the length of the route and maximizing the margin of safety can be simultaneously important, Mittal et al. [22] used a hybrid multi-objective evolutionary algorithm to optimize the flight distance and risk factor simultaneously, and thus generated a set of Pareto-optimal routes. However, the majority of existing studies mainly employs the penalty function based methods to handle the constraints and cannot always achieve the feasible route during every computation. Different from these existing works, we formulate the UAV route planning as the constrained single objective optimization problem in the 3-D environment, and generate the feasible route by using a variant of constrained DE algorithm.

During the last few years, several DE-based methods were proposed for the constrained optimization problems [30–38]. These methods adopt various constraint-handling strategies and can be grouped into the following categories [30]: (1) methods based on preserving feasibility of solutions, (2) methods based on penalty functions, (3) methods, which make a clear distinction between feasible and infeasible solutions, and (4) other hybrid methods. Inspired by the fuzzy control theory, Takahana et al. [35,38] proposed the α constrained method and the ε constrained differential evolution algorithm (εDE). Due to the excellent performance of DE on unconstrained optimization problems and the superior constraint-handling ability of α constrained method, Wang et al. [31,32] designed a hybrid DE algorithm with level comparison (DELC) for the constrained optimization by incorporating the α constrained method into DE. In this paper, a novel UAV route planning method is proposed by combining the DE algorithm and an improved level comparison strategy. Our proposed route planning algorithm is easy to implement and numerical experiments demonstrate its effectiveness, efficiency and robustness.

The rest of this paper is organized as follows. Section 2 describes the UAV route planning problem, including the route representation, the objective function and multiple constraints in the realistic scenarios. In Section 3, the improved DE algorithm is described in detail, and a detailed implementation procedure to solve the route planning problem is also presented. Experiments and comparisons with some existing constrained algorithms are provided in Section 4. Further discussion and comparisons are presented in Section 5, including the influence of some parameters as well as the comparison with the penalty function based methods and other DE variants. Finally, Section 6 concludes with a brief summary of this paper.

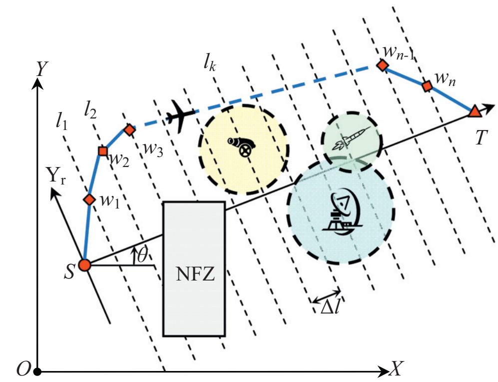

Fig. 1. Schematic diagram of UAV route.

2. Problem description

2.1. Route representation

As to the problem of UAV global route planning considered in this paper, we assume that the flight environment is fixed and all obstacles and threat areas are known a priori. The mission of the UAV is to fly through a high-threat region as safely as possible, and meanwhile, with the least time consumption.

In the global earth-surface inertial reference frame S_g-$OXYZ$, which puts the origin of coordinates O on a certain point on the ground and uses three orthogonal directions as the X, Y, Z axes, where the X, Y axes are in the horizontal plane and the Z axe is in the vertical direction, the labels $S:(x_S, y_S, z_S)^T$ and $T:(x_T, y_T, z_T)^T$ identify the starting and target points, respectively, as is shown in Fig. 1, and various danger zones, forbidden flying areas and terrain obstacles exist in the mission region. The offline route planning is to generate a short and safe route from S to T, while satisfying the constraints. The UAV route can be described by a point set consisting of N waypoints besides S and T as $P_{UAV} = \{S, p_1, p_2, \cdots, p_N, T\}$, which can be determined by n control points $w_k:(x_k, y_k, z_k)^T$ and a predefined trajectory smooth strategy. It plays a key role of the route parameterization in the global route planning problem. Bezier curves have been widely adopted when computing smooth, dynamically feasible trajectories for the UAV [4,10,11,14,15]. Employing Bezier curve, the route can be represented using a relatively smaller number of parameters than using a complete geometric description of the route. However, the construction of Bezier curves needs all the coordinates of the corresponding control points, including horizontal ordinates and vertical coordinates.

In order to reduce the dimension of the problem, a new rotated coordinate frame S_r-$SX_rY_rZ_r$ shown in Fig. 1 is established using $\overline{ST}$ as the new X-axis [19,19,21]. Given the straight distance from S to T is L, coordinates of the points S and T are $(0, 0, z_S)^T$ and $(0, L, z_T)^T$ in the coordinate frame S_r-$SX_rY_rZ_r$. The coordinate transformation between the two reference systems is performed according to:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x^r \\ y^r \\ z^r \end{pmatrix} + \begin{pmatrix} x_S \\ y_S \\ 0 \end{pmatrix} \tag{1}$$

where $(x, y, z)^T$ and $(x^r, y^r, z^r)^T$ are coordinates of the same point in the original global reference frame and the rotated frame,