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Three-dimensional path planning for unmanned aerial vehicle based on interfered fluid dynamical system

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Abstract This paper proposes a method for planning the three-dimensional path for low-flying unmanned aerial vehicle (UAV) in complex terrain based on interfered fluid dynamical system (IFDS) and the theory of obstacle avoidance by the flowing stream. With no requirement of solutions to fluid equations under complex boundary conditions, the proposed method is suitable for situations with complex terrain and different shapes of obstacles. Firstly, by transforming the mountains, radar and anti-aircraft fire in complex terrain into cylindrical, conical, spherical, parallelepiped obstacles and their combinations, the 3D low-flying path planning problem is turned into solving streamlines for obstacle avoidance by fluid flow. Secondly, on the basis of a unified mathematical expression of typical obstacle shapes including sphere, cylinder, cone and parallelepiped, the modulation matrix for interfered fluid dynamical system is constructed and 3D streamlines around a single obstacle are obtained. Solutions to streamlines with multiple obstacles are then derived using weighted average of the velocity field. Thirdly, extra control force method and virtual obstacle method are proposed to deal with the stagnation point and the case of obstacles' overlapping respectively. Finally, taking path length and flight height as sub-goals, genetic algorithm (GA) is used to obtain optimal 3D path under the maneuverability constraints of the UAV. Simulation results show that the environmental modeling is simple and the path is smooth and suitable for UAV. Theoretical proof is also presented to show that the proposed method has no effect on the characteristics of fluid avoiding obstacles.

1. Introduction

Path planning is one of the most important technologies for autonomous flight of unmanned aerial vehicle (UAV). Nowadays, the application of UAV is extending from high-altitude flight to low or super low-altitude, where the impact of terrain will be the key factor to be considered. Since 3D path planning

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can give full play to the maneuverability of UAV and has an important role in military or civilian areas such as low altitude penetration, low altitude reconnaissance or disaster perception, many researchers in this area have carried out in-depth researches.

To generate a suitable path for UAV, path planning restricted by complex terrain should consider not only the potential impact of terrain on flight safety but also the performance constraints on UAV.

Probabilistic roadmap (PRM)[1] and rapidly-exploring random tree(RRT)[2] have been applied to 3D path planning for its efficiency, but both of them are carried out by spatial discretization. When facing to complex environment, the modeling is complex and the paths of these methods are composed of roadmaps or waypoints, which are not smooth enough for UAV. In addition, in a very cluttered environment, the RRT may fail to find a path.[3]

Methods based on intelligent computing like ant colony algorithm (ACO)[4], evolutionary algorithm (EA)[5] and particle swarm optimization (PSO)[6] have strong search capabilities. However, the algorithm performance degrades with environmental complexity and may fall into local minima. Combination of these methods with other means to improve algorithm performance and handle more complex situations is a research hotspot at present.[7–9]

In order to obtain 3D path which satisfies the maneuverability constraints on UAV, many new methods have been proposed recently. Frazzoil et al.[10] proposed a novel Maneuver-Based planning method, by which several motion primitives can be generated based on the dynamics of UAV and the path is obtained by selecting different motion primitives and connecting them up. This method is applied to real time path planning for its high efficiency[11], but the deficiency is restricting the flight maneuver within a finite number of motion primitives. Using the optimal control theory to solve path planning problem can easily transform various constraints and optimal index into mathematical expressions but the solution demands large computation. Although the application of some new solutions such as pseudospectral method[12] and nonlinear trajectory generation[13] can share the computation burden, for complex terrain constraints, the 3D path planning problem is still complex with this method. Nikolos et al.[14] used B-spline curves to simulate the 3D flight trajectory of aircraft, and then used an evolutionary algorithm to optimize the B-spline curve control points. This method can generate smooth path, but the terrain used for simulation is relatively simple, generated only by mathematical functions. Mattei and Blasi[15] defined a weighted and oriented graph which indicates the minimum length trajectories between selected nodes in planning space and the optimal path between any two nodes can be optimized by searching algorithms. However, to build the graph, computational efficiency needs further improvement for multiple problems of quadratic programming.

Artificial potential field (APF)[16] is initially proposed and used in collision avoidance for ground robot. In recent years, it is gradually applied to path planning for UAV.[17,18] This method is simple in principle and has a small amount of calculation, but it may easily converge to local minima in global planning. Many researchers have proposed approaches to solve the problem[19–21], of which the most representative one is stream function.[22,23] It uses the concept of hydrodynamic to establish potential filed in which local minima can be avoided. The method is able to plan smooth path in a short time and shows good performance in the flight test.[24] However, the concept of stream function only exists in 2D flow and it cannot be applied to 3D path planning. Moreover, according to the current research result, obstacles can only be circular.[25]

To expand the stream function method into three dimensions, the method based on fluid flow[26] is proposed recently. Based on the principles of a fluid flowing around objects and the phenomenon of stream flow from start to end, 3D smooth path that satisfies the maneuverability constraints on UAV can be generated in two ways, which are analytical method and numerical method. The analytical method has less calculation but can only handle spherical obstacles, which are not sufficient to model the complex terrain environment. The numerical method can handle more complex terrain and obstacles, but it needs more preprocessing and computational costs.

To overcome the shortcomings of analytical and numerical methods, on the basis of the method in Ref.,[26] in this paper we model the complex terrain environment as spherical, conical, cylindrical and parallelepiped geometry and combinations thereof and study the analytical path planning method in the presence of obstacles in these shapes. Simulation results demonstrate that the proposed method can plan smooth path which satisfies the maneuverability constraints on UAV in complex environment. The method not only keeps the advantages of analytical method with small amount of calculation, but also greatly expands the application of the method of fluid flow.

2. Path planning methods based on fluid computing

As two kinds of methods based on fluid computing, the basic idea of stream function and the method based on fluid flow is to transform the path planning problem into solving streamlines for fluid flow avoiding obstacles. Learning from the phenomenon of flow around obstacles, the terrain is considered as boundary conditions. Flow field distribution in the planning area is calculated by using fluid mechanics, then the streamlines in the field are taken as flight paths for UAV. In fluid mechanics, the problem of flow around obstacles is described by governing equations and boundary conditions,[27] and the controlling equation of potential flow is described as Eq. (1).

$$\nabla^2 \Phi = 0 \tag{1}$$

The boundary conditions of Eq. (1) are as follows:

$$\text{On the surface of obstacles}: \frac{\partial \Phi}{\partial \boldsymbol{n}} = 0 \tag{2}$$

$$\text{At infinite distance}: \nabla \Phi = \boldsymbol{u}_\infty \tag{3}$$

where ∇ denotes the vector differential operator, Φ represents velocity potential, $\boldsymbol{n}$ is unit normal vector along outward on the surface of obstacles and $\boldsymbol{u}_\infty$ is the velocity of flow at infinity. Eq. (1) is Laplace's equation, which describes the irrotational and incompressible characteristics of a potential flow. As the solution of equation, Φ is harmonic function and satisfies extremum principle.[22] Because Φ can only reach the extremum on the boundary, it will avoid local minima. Eq. (2) is an equation of boundary and it shows impenetrable constraint of obstacles, which is the normal velocity on the surface of obstacles vanishes. According to Eq. (2), the normal compo-