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UAV feasible path planning based on disturbed fluid and trajectory propagation

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Abstract In this paper, a novel algorithm based on disturbed fluid and trajectory propagation is developed to solve the three-dimensional (3-D) path planning problem of unmanned aerial vehicle (UAV) in static environment. Firstly, inspired by the phenomenon of streamlines avoiding obstacles, the algorithm based on disturbed fluid is developed and broadened. The effect of obstacles on original fluid field is quantified by the perturbation matrix, where the tangential matrix is first introduced. By modifying the original flow field, the modified one is then obtained, where the streamlines can be regarded as planned paths. And the path proves to avoid all obstacles smoothly and swiftly, follow the shape of obstacles effectively and reach the destination eventually. Then, by considering the kinematics and dynamics equations of UAV, the method called trajectory propagation is adopted to judge the feasibility of the path. If the planned path is unfeasible, repulsive and tangential parameters in the perturbation matrix will be adjusted adaptively based on the resolved state variables of UAV. In most cases, a flyable path can be obtained eventually. Simulation results demonstrate the effectiveness of this method.

1. Introduction

Path planning refers to plan an optimal path from the starting point to the destination while avoiding obstacles. It is one of the key technologies to improve the autonomy level of unmanned aerial vehicle (UAV). And the planned path should satisfy the following conditions: ① safety, i.e., UAV can avoid all obstacles successfully; ② feasibility, i.e., the planned path should satisfy dynamic constraints and can be tracked by the control system; ③ optimization, i.e., the optimal path is obtained by minimizing the cost function; ④ high computational efficiency, i.e., the complexity of the algorithm is acceptable. Traditional methods usually focus on two-dimensional (2-D) path planning, which is easy to achieve. However, with the development of UAV maneuverability and the demands for low-altitude and terrain-following flight, three-dimensional (3-D) path planning is gaining increasing attention.

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Traditional geometric approaches, based on searching waypoints in digital maps, are improved to solve the 3-D path planning problem. The upgrade of Dubins method[1] extends the Dubins car with altitude. And the time-optimal trajectories are characterized through the Pontryagin maximum principle. Probabilistic roadmaps (PRMs) and D^* Lite[2] are combined for path planning with stereo-based occupancy mapping. The improved rapidly-exploring random tree (RRT)[3] produces a time parameterized set of control inputs to make UAV move from the initial point to the destination, which proves to be efficient for 3-D path planning. However, the calculation of these geometric algorithms tends to increase exponentially if the planning space enlarges. Besides, the planned path may be not smooth enough for UAV to track.

Methods based on potential field are utilized to meet the real-time requirements of path planning. Artificial potential field (APF) method[4–7] has the advantages of simple principle and small amount of computation. Yet local minimum exists when the vehicle enters into a concave area. Besides, there may be some oscillation of the path if it enters into the narrow gap between two obstacles. Virtual force (VF) method[8,9] is utilized for real-time path planning. The agent is taken as a particle in 3-D environment and the resultant force consists of two parts: the attractive force pointing to the target point and the repulsive one forcing UAV away from obstacles. The biggest advantage of this method is its ability of real-time computation. However, the definition of repulsive force is not objective enough as it ignores the shape of obstacles. Besides, it is hard to obtain a feasible path sometimes even if the magnitude of attractive or repulsive force is regulated.

The intelligent algorithms, e.g., particle swarm optimization (PSO),[10] evolutionary algorithms (EA)[11] and ant colony algorithm (ACO)[12] are also widely used to plan the optimal path by minimizing the cost function. These methods can be easily employed in different scenarios, but it is possible to trap in a local optimum. Meanwhile, the process of optimization is time-consuming. Therefore, the intelligent methods are improved or combined with other methods to relieve the abovementioned drawback.[13–16] By combing the improved differential evolution method and the level comparison algorithm,[13] an optimal path is eventually obtained in 3-D environment. Pehlivanoglu[16] proposed the multi-frequency vibrational genetic method for path planning, where the initial population is defined by the clustering method and Voronoi diagram. However, the computation efficiency of these intelligent algorithms remains unsatisfactory, especially in 3-D complex environment. Besides, the distance between the adjacent waypoints by these methods is too large, making the planned path unsmooth. As a result, extra strategy of smoothing path is usually needed.

In addition, many novel methods are proposed in order to plan a feasible or smooth path. A novel dynamic system approach[17] is presented for real-time obstacle avoidance and the parameterized modulation of the dynamical system increases the agent's reactiveness, but this method is more suitable for robotic platform. Maneuver-based motion planning method[18] generates a set of trim states and the corresponding maneuver paths, which are based on UAV nonlinear dynamic model and performance constraints. By generating the trim-maneuver library, the complicated path planning is then turned into a simple hybrid optimization problem. Yet only discrete and finite design variables are offered here. The core paths graph (CPG) algorithm[19] calculates the CPG where arcs are minimum-length trajectories satisfying geometrical constraints, and searches the optimal trajectory between two arbitrary nodes of the graph. However, multiple quadratics should be resolved, resulting in low computational efficiency.

In recent years, one kind of methods based on fluid computation[20–23] is gaining more attention because of the planned smooth paths. The path can be generated by two ways:[20,21] the analytical method, which has small amount of calculation but only applies to sphere obstacle; the numerical method, which applies to cases with various obstacles but has the time-consuming drawback. In our previous work, a novel bio-inspired approach based on interfered fluid dynamical system (IFDS)[24,25] is presented for path planning. Unlike other bio-inspired methods, the biggest advantage of this method is its high computational efficiency and smooth planned paths. This method imitates the phenomenon that water in river avoids rocks smoothly and reaches the destination eventually. As the streamlines obtained by simple formula still have certain optimizing properties, they can be available as planned paths for UAV. However, the distribution of streamlines is not wide enough, and therefore sometimes it is hard to obtain a feasible path, even if the reaction parameter is adapted. Besides, the aircraft dynamics are not taken into account.

To solve the above problems, the method based on disturbed flow is developed to generate more widely distributed streamlines by combing the VF method[8] and the interfered fluid dynamical system.[24] Although the physical characteristics of the modified streamlines are broadened, they still conform to the basic properties of fluid flow, i.e., smoothness, impenetrability and accessibility. Therefore, what we only focus on is to adjust repulsive or tangential parameters when the planned path is unfeasible sometimes. Considering most algorithms do not fully consider UAV dynamics and kinematics, trajectory propagation[26,27] is employed here to judge the feasibility of path and to adjust parameters adaptively.

2. Environment modeling

Fig. 1 illustrates a very common phenomenon in the nature: when there are no rocks in the river, water can flow towards the destination straightly; when there are some rocks, running water can still avoid them smoothly and reach the destination eventually. There are some commonalities between this phenomenon and path planning problem. Inspired by this observation, the simple rules are imitated in this paper to solve UAV path planning problem: rocks in river are regarded as

Fig. 1 Running water avoiding rocks.