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Real-time path planning of unmanned aerial vehicle for target tracking and obstacle avoidance in complex dynamic environment

Peng Yao [a,b], Honglun Wang [a,b,*], Zikang Su [a,b]

[a] *School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China*
[b] *Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing 100191, China*

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ABSTRACT

According to the tactical requirements of unmanned aerial vehicle (UAV) for tracking target and avoiding obstacle in complex dynamic environment, a three-dimensional (3D) real-time path planning method is proposed by combing the improved Lyapunov Guidance Vector Field (LGVF), the Interfered Fluid Dynamical System (IFDS) and the strategy of varying receding-horizon optimization from Model Predictive Control (MPC). First, in order to track the moving target in 3D environment, the LGVF method is improved by introducing flight height into the traditional Lyapunov function, and the generated velocity can guide UAV converge gradually to the limit cycle in horizontal plane and the optimal height in vertical plane. Then, the IFDS method imitating the phenomenon of fluid flow is utilized to plan the collision-free path. To achieve the mission of tracking moving target and avoid static or dynamic obstacle at the same time, the guidance vector field by LGVF is taken as the original fluid of IFDS. As the fluid system still remains stable under the influence of obstacles, the disturbed streamline from the interfered fluid can be regarded as the planned path. Third, as the quality of route is mainly influenced by the repulsive and tangential parameters of IFDS, the real-time suboptimal route can be planned by the varying receding-horizon optimization according to the predicted motion. The experimental results prove that the proposed hybrid method is applicable to various dynamic environments.

1. Introduction

Path planning plays an important role in enhancing the ability of autonomous flight of unmanned aerial vehicle (UAV). By finding a global optimal route offline, the traditional two-dimensional (2D) path planning is popular in static or known environment [1–3]. But the actual flight environment of UAV is usually dynamic and unknown, where a feasible path should be planned online by dealing with various dynamic situations. Besides, compared to a 2D path, a three-dimensional (3D) route is more applicable to low-altitude and terrain-following flight. In addition, UAV needs to track static or moving target and avoid static or moving obstacles at the same time in many cases, but most methods only consider one above-mentioned tactical mission or assume the environment to be simple [4–8]. Therefore, the challenging real-time path planning technology in 3D complex environment is studied in this paper.

Many studies have been carried out by researchers aiming at the problem of target tracking. The theory of dynamic programming is utilized in Ref. [7], where the distance between UAV and target keeps constant by minimizing the position error covariance while ignoring the relative angle. In Ref. [8], partially observable Markov decision process (POMDP) is employed to guide UAV trace the moving target. Lee et al. [9] propose a method based on the backstepping theory, where the path globally approximates to the target. Lawrence et al. [10] construct the Lyapunov guidance vector field (LGVF) centering at the target, where UAV will converge to the limit cycle over the moving target. Chen et al. [11] present the tangent guidance vector field (TGVF) to find the shortest path when the distance between UAV and target is bigger than the expected distance. But it is invalid when UAV is inside the expected cycle. Hence a hybrid method is developed in Ref. [12], where TGVF and LGVF are separately utilized when UAV is outside or inside the expected cycle. However, the above algorithms are mainly effective for 2D planning.

According to the problem of obstacle avoidance, the current algorithms can be summarized to the following five kinds: heuristic search based method [1], e.g. A* algorithm and its improved

* Corresponding author at: School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China. Tel.: +86 10 82317546.
E-mail address: hl_wang_2002@126.com (H. Wang).

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methods (D* and D* Lite methods); optimization algorithm [2,3,6,13], e.g. mixed integer linear programming (MILP), intelligent algorithms (e.g. Particle Swarm Optimization, Gravitational Search Algorithm, Genetic Algorithm, etc.); probabilistic programming [14], e.g. Rapidly-exploring Random Tree (RRT) and Probabilistic Roadmaps (PRM); potential field based method [15–17], e.g. Artificial Potential Field (APF), Virtual Force (VF) and the method based on stream function; Roadmap based method [18], e.g. Voronoi Map. In order to avoid the moving threats, APF is improved by introducing the relative velocity into the potential-energy function [19]. Model Predictive Control (MPC) is utilized in Refs. [20,21] to plan a suboptimal path in real time. These methods may be efficient in planning a real-time 2D path, but their computational efficiency will decrease substantially when utilized in 3D environment. Besides, the quality of path e.g. smoothness is unsatisfactory. Therefore, a novel path planning method based on Interfered Fluid Dynamical System (IFDS) is proposed in our previous work to plan a collision-free path [22,23]. This method will not change the stability of the original system, i.e. the planned path can avoid various obstacles or threats and reach the target eventually. However, the target tracking mission as well as the real-time optimization of the route is not taken into consideration.

The actual flight environment of UAV is complicated, where UAV should avoid static obstacles or moving threats and track moving target at the same time. Compared to standard path planning in simple environment, this technology is much more complicated. In Refs. [12,24], TGVF and LGVF are combined for target tracking, and only some simple rules are then implemented for avoiding circle obstacles in 2D environment. In Ref. [25], the POMDP method is utilized where the features of target tracking and obstacle avoidance can be incorporated into this POMDP framework by plugging in their appropriate models. And the state space, the action space, the conversion strategy and the objective function can all be formulized, but it is only suitable for 2D environment. Under the constraints of terrain occlusions and airspace limitations, Shaferman et al. [28] utilized the genetic method to optimize the target-tracking route in urban environment, while the future motion of target is ignored.

On the basis of above analysis, a single method cannot usually meet the requirements of target tracking and obstacle avoidance simultaneously. And the computation efficiency and the route quality of most methods are still unsatisfactory in 3D environment. Therefore, a three-dimensional dynamic path planning method is proposed in this paper by combing LGVF and IFDS, and the strategy of varying receding-horizon optimization from MPC is also utilized to obtain the suboptimal path in real time. First, on the basis of the standard LGVF, the flight height is introduced into the Lyapunov function which proves to be stable. Taking into account UAV dynamic constrains, the velocity of the guidance vector field will guide UAV to track static and moving target in 3D environment. Second, the guidance vector field by LGVF is taken as the original fluid of IFDS, which imitates the phenomenon of fluid flow. And the disturbed velocity can guide UAV avoid obstacles and track target at the same time. Third, inspired by the MPC theory, the suboptimal route is obtained by adjusting the repulsive and tangential parameters of IFDS in the varying receding horizon. In the objective function, the sub-objective functions which respectively describe performances of target tracking and obstacle avoidance are incorporated.

The rest of this paper is organized as follows. Section 2 models the problem of path planning. The improved LGVF is then described in Section 3. In Section 4, the IFDS method is introduced. The varying receding-horizon optimization strategy is illustrated in Section 5. In Section 6, the experimental results are analyzed. Finally Section 7 draws the conclusion of this paper.

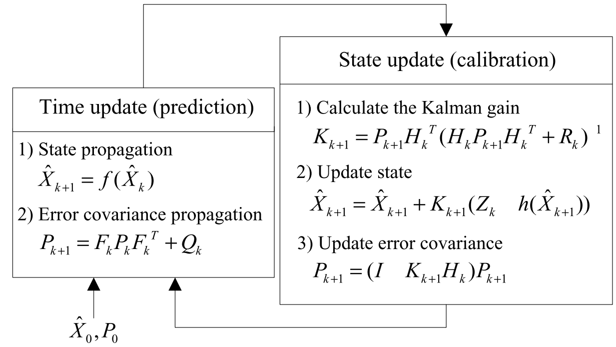

Fig. 1. The process of EKF.

2. Modeling of path planning

2.1. Problem description

In this paper, the mission of target tracking and obstacle avoidance are considered simultaneously for the dynamic path planning problem, which can be regarded as the real-time optimization problem under constraints. The future motion of threat or target should be predicted according to the real-time detection information by UAV. Then the constraints of path planning are confirmed on the basis of UAV maneuvering characteristics and environmental information. Finally the route satisfying the certain optimization index under constraints is generated quickly.

In the planning space C, any point can be expressed as $P = (x, y, z)$. The initial position of target is $P_{t0} = (x_{t0}, y_{t0}, z_{t0})$, the final point of target $P_{tf} = (x_{tf}, y_{tf}, z_{tf})$, the initial state i.e. the start point of UAV $P_0 = (x_0, y_0, z_0)$, and the final state $P_f = (x_f, y_f, z_f)$. The process of path planning is finding the flyable waypoints and connecting them to form the route.

2.2. State prediction by Extended Kalman Filter (EKF)

We assume that the acceleration speed of target or threat is variable, so the traditional Kalman Filter does not apply to state prediction. In this paper, EKF [26] is utilized to predict the future motion of target or threat. The position and velocity of target or threat are taken as the motion state i.e. $\boldsymbol{X}_k = [x_k, y_k, z_k, v_{xk}, v_{yk}, v_{zk}]^{\mathrm{T}}$; the position is taken as the corresponding observed value i.e. $\boldsymbol{Z}_k = [x_k, y_k, z_k]^{\mathrm{T}}$. Hence the state equation and observation equation of EKF are expressed as follows:

$$\begin{cases} \boldsymbol{X}_{k+1} = \boldsymbol{f}(\boldsymbol{X}_k) + \boldsymbol{w}_k \\ \boldsymbol{Z}_{k+1} = \boldsymbol{h}(\boldsymbol{X}_k) + \boldsymbol{v}_k \end{cases} \tag{1}$$

where $\boldsymbol{f}$ and $\boldsymbol{h}$ are the state equation and observation equation of moving threat or target; $\boldsymbol{w}_k$ and $\boldsymbol{v}_k$ are the zero-mean Gaussian process noise and observation noise i.e. $p(\boldsymbol{w}) \sim N(0, \boldsymbol{Q})$ and $p(\boldsymbol{v}) \sim N(0, \boldsymbol{R})$. $\boldsymbol{Q}$ and $\boldsymbol{R}$ are the corresponding covariance matrixes. Fig. 1 describes the process of EFK. The state matrix $\boldsymbol{F}_k$ and observation matrix $\boldsymbol{H}_k$ are the Jacobian matrix calculated by the partial derivative of $\boldsymbol{f}$ and $\boldsymbol{h}$ respectively:

$$\boldsymbol{F}_k = \begin{bmatrix} \frac{\partial f_1}{\partial x_k} & \cdots & \frac{\partial f_1}{\partial v_{zk}} \\ \vdots & & \vdots \\ \frac{\partial f_6}{\partial x_k} & \cdots & \frac{\partial f_6}{\partial v_{zk}} \end{bmatrix}, \qquad \boldsymbol{H}_k = \begin{bmatrix} \frac{\partial h_1}{\partial x_k} & \cdots & \frac{\partial h_1}{\partial v_{zk}} \\ \vdots & & \vdots \\ \frac{\partial h_3}{\partial x_k} & \cdots & \frac{\partial h_3}{\partial v_{zk}} \end{bmatrix} \tag{2}$$

2.3. UAV performance constraints

UAV performance should be modeled as the constraints of path planning to ensure the feasibility of route. In this paper, UAV is assumed to fly at the constant cruising speed V_0. The minimum and