UAV Autonomous Collision Avoidance Method Based on Three-dimensional Dynamic Collision Region Model and Interfered Fluid Dynamical System

Chang LIU1,2, Hong-lun WANG1,2,a,* and Peng YAO1,2

1School of Automation Science and Electrical Engineering, Beihang University, Beijing, China
2Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing, China

ahl_wang_2002@126.com
*Corresponding author

Keywords: Collision detection, Collision decision, Three-dimensional collision region, Path re-plan, Modeling, UAV.

Abstract. Aiming at the problem of 3D collision avoidance for unmanned aerial vehicle (UAV), this paper proposed a UAV collision detection, collision decision and path re-planning method. Firstly, traditional methods calculate collision regions using certain threshold value of distance or time. In order to improve the shortcoming of existing methods, this paper considered maneuver information of both UAV and aerial intruder. Models of three-dimensional collision regions were presented. The proposed regions models could be used for UAV to successfully detect collision and make an appropriate collision decision. Secondly, a collision decision method based on the proposed regions and interfered fluid dynamical (IFDS) algorithm was present. UAV autonomously made collision decision by using the proposed regions models, and chose an appropriate maneuverer mode to avoid collision. Then the IFDS algorithm was applied to re-plan UAV’s flight path. Finally, the simulation results demonstrate the effectiveness of the presented method.

Introduction

In the last few decades, the unmanned aerial vehicle (UAV) has been widely used for some military and civilian fields. UAVs are able to carry out some tasks in dangerous or dirty environment. They are trending to replace the traditional manned vehicle in some fields [1]. Meanwhile, as the increasing applications, the intelligent and autonomous level of UAVs is a very important factor to determine that if UAVs can carry out tasks with manned aircrafts together in the unknown environment. In order to accomplish task successfully, safety flight is the basic requirement. UAVs should have various technologies, e.g. detecting and modeling environment, detecting collision, deciding collision avoidance strategy and re-planning flight path. These aim to ensure UAVs safety flight, to choose appropriate collision avoidance time and maneuver flight mode.

In traditional methods, collision detection and collision avoidance decision are usually depend on several predefined values of time or distance. Collision avoidance system or pilot judges the level of dangerous of collision by comparing current and predefined values of time or distance. For example, traffic alert and collision avoidance system (TCAS) and automatic dependent surveillance broadcast (ADS-B) [2], which are widely used in the civil aviation field, both defined collision regions by predefined different values in the scale of different levels of safety flight.

For collision avoidance research of UAVs or other aircrafts, Carbone et al. [3] presented a novel decision-making algorithm for pair wise non-cooperative aircraft mid-air collision avoidance. And intruder is modeled as a sphere with radius R (considered as safety bubble). Luongo et al. [4] proposed an analytical algorithm for collision avoidance based on the consideration of a cylindrical safety bubble. With the choice of specified values for cylinder geometric dimensions, the cylinder is used to require on autopilot command rate and maneuver settling time. Amirreza et al. [5] proposed a method combined conflict prediction and resolution. They consider individual UAV to be surrounded by three virtual spheres which specify distinct levels of safety constraints. Overall, most researchers...
define some 2D or 3D zones such as circle, ellipse, or sphere, cylinder, ellipsoid based on specific value of time or distance to indicate the level of dangerous between aircrafts. So this paper proposed collision regions based on maneuver information of both UAV and aerial intruder, and also considered UAV maximum maneuverability constraint.

Autonomous flight path re-planning is one of the critical technologies for collision avoidance system to re-plan an optimal flight path while avoiding obstacles or intruders. With the development of UAV maneuverability and the demands for autonomous flight, flight path re-planning is gaining increasing attention. The rapidly-exploring random tree (RRT) [6] has been applied to 2D and 3D flight path re-planning which proves to be efficient for 2D and 3D flight path re-planning. However, in a much cluttered environment, the RRT may fail to find a flight path. Heuristic search methods (e.g. A* or D* algorithm) [7, 8], intelligent algorithms (e.g. genetic algorithm, particle swarm optimization, ant colony algorithm et al.) are also widely used to plan the flight path. And these methods are improved or combined with other methods to relieve their drawback [9]. Meanwhile, methods based on potential field are utilized to meet the real-time requirements of path re-planning. Artificial potential field (APF) method [10] has the advantages of simple principle and small amount of computation. Yet local minimum exists when the vehicle enters into a concave area.

In this paper, the interfered fluid dynamical system (IFDS) algorithm is used for UAV to re-plan a 3D collision-free path, by imitating the phenomenon of fluid disturbance. 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 re-planned paths for the problem of UAV collision avoidance.

Collision Detection by Collision Regions Modeling

For most collision avoidance system, the process of collision avoidance can be divided into three parts: collision detection, collision avoidance decision and collision avoidance maneuver. Collision detection algorithm is the basic algorithm for the whole process of collision avoidance. If an alert from collision detection algorithm is too early, UAVs maybe take some unnecessary maneuvers, which will affect the flight plan or flight mission. But if the alert is too late, UAVs maybe don’t have enough time to avoid intruders. This is very dangerous for UAVs. Therefore, when intruders are far away from UAVs (They will collide after a time.), UAVs need use some flight re-planning algorithms to re-plan the flight path. When intruders are near from UAVs, UAVs must use their maximum maneuverability to avoid the intruders. Overall, the appropriate time or appropriate distance for maneuver mode of collision avoidance decision is very important.

On the basis of above consideration, 2D collision regions are proposed in our previous work [11]. However, compared to simple 2D path, a 3D path is more effective in improving UAVs capabilities of collision avoidance. Hence, in this paper, we propose five 3D collision regions to help UAVs choose the right collision avoidance maneuvers. The definitions of five 3D collision regions are as follow.

Collision Region: The minimum safe distance, between UAV position $P_\text{u}$ and an intruder position $P_\text{m}$, is defined as $D_L$. The collision region is defined as a sphere:

$$
(X - X_\text{u})^2 + (Y - Y_\text{u})^2 + (Z - Z_\text{u})^2 = D_L^2
$$

where $\left(X_\text{u}, Y_\text{u}, Z_\text{u}\right)$ is the UAV’s coordinate.
No-maneuver Collision Region: Assume flight modes of a UAV and an intruder are both uniform rectilinear motion. The velocity of the UAV is \( v_u \), and the velocity of the intruder is \( v_m \). The no-maneuver collision region is defined as:

\[
[X - X_{P_u}(t_0)]^2 + [Y - Y_{P_u}(t_0)]^2 + [Z - Z_{P_u}(t_0)]^2 = D_0^2
\]

where \( \{X_{P_u}(t_0), Y_{P_u}(t_0), Z_{P_u}(t_0)\} \) is the UAV’s coordinate. When \( t = t_0 \), the distance between UAV and intruder is \( D(t) = D_0 \); When \( t = t_0 + \Delta t \) \((0 < \Delta t < \infty)\), the distance between UAV and intruder is \( D(t) = D_L \).

Remark 1. It is seen from the above definition that if the UAV is considered as static, the flight path of intruder is tangential to collision region.

Remark 2. Because the flight modes of UAV and intruder are both uniform rectilinear motion, the boundary of no-maneuver collision region is parallel to relative velocity \( v_r \) of UAV and intruder.

Maximum Maneuverability Collision Region: Assume that after \( t = t_0 \), UAV will move with uniform speed in circle by its maximum maneuverability; and the intruder always move with uniform speed in a straight line. Maximum maneuverability collision region is defined as:

\[
[X - X_{P_u}(t_0)]^2 + [Y - Y_{P_u}(t_0)]^2 + [Z - Z_{P_u}(t_0)]^2 = D_0^2
\]

where \( \{X_{P_u}(t_0), Y_{P_u}(t_0), Z_{P_u}(t_0)\} \) is the UAV’s coordinate. When \( t = t_0 \), the distance between UAV and intruder is \( D(t) = D_0 \); When \( t = t_0 + \Delta t \) \((0 < \Delta t < \infty)\), the distance between UAV and intruder is \( D(t) = D_L \).

Remark 3. The modeling idea of maximum maneuverability collision region is: at the start, UAV and intruder are both moving with uniform speed in a straight line; when the intruder arrives at the boundary of maximum maneuverability collision region, the UAV moves immediately with uniform speed in circle by its maximum maneuverability. On this condition, the UAV can exactly avoid a collision with the intruder.

Non-escape region: Assume an intruder suddenly enters the region surrounding UAV at the time \( t_0 \), and the intruder always moves with uniform speed in a straight line after the time \( t_0 \). If the UAV whether or not takes some maneuvers, even using its maximum maneuverability, it still cannot avoid a collision. The initial position of intruder at the time \( t_0 \) is the boundary of non-escape region.

Remark 4. According to the above definitions, we know that non-escape region is intersection of no-maneuver collision region and maximum maneuverability collision region. So the non-escape region could be used to make collision decision, and it doesn’t increase the amount of computations.

Safe flight envelope: Non-escape region is based on a fixed angle \( \varphi_m \) of the intruder’s speed. If we change the angle of the intruder’s speed in the scale of \( 0 \sim 2\pi \), we can calculate different non-escape regions. All the non-escape regions are unioned together into a safe flight envelope.

Remark 5. Safe flight envelope is a boundary of the region surrounding UAV which can be used to judge whether or not UAV can avoid a collision with the intruder. If the intruder enters the safe flight envelope, collision between UAV and intruder must have happened.
Collision Decision by Proposed Collision Regions

In this paper, when UAV detects that an intruder enters its surrounding region, the UAV will make a collision decision using the proposed collision regions. If intruder is out of no-maneuver collision region, it means that UAV and the intruder will not collide with each other in the future. So in this condition, the UAV needn’t take any collision maneuver. If intruder enters no-maneuver collision region and is far away from maximum maneuverability collision region, it means that UAV and the intruder will collide with each other in the future. And the UAV need re-plan flight path to avoid the collision. In this paper, we used interfered fluid dynamical (IFDS) algorithm [12] to calculate the new flight path for UAV. And the IFDS algorithm is described in the following part.

If intruder enters no-maneuver collision region and is near the boundary of maximum maneuverability collision region, it means that UAV is dangerous now. The UAV must move immediately with uniform speed in circle by its maximum maneuverability. We calculate maximum maneuverability collision regions of UAV turning right and left respectively. When the intruder is near one of boundaries of maximum maneuverability collision regions, the UAV will turn the other direction of motion. If intruder enters non-escape region or safe flight envelope, because of the constraints of UAV (e.g. maximum velocity, maximum turn rate and maximum flight-path angle), the UAV whether or not take some maneuvers, even using its maximum maneuverability, cannot avoid a collision with the intruder.

Path Re-planning Method Based on IFDS Algorithm

If there is no intruder in the region surrounding UAV, the original streamlines, i.e., UAV path is supposed to be straight lines from the start points to the target point with a constant velocity. By modifying the initial fluid with the modulation matrix, we will obtain the inferred fluid where the streamline can be taken as planned path. The velocity of the initial fluid is

\[
\mathbf{u} = \left[ \frac{v_0(x-x_t)}{d(P,P_t)}, \frac{v_0(y-y_t)}{d(P,P_t)}, \frac{v_0(z-z_t)}{d(P,P_t)} \right]^T
\]

(4)

where \( d(P,P_t) \) is the distance between \( P \) and \( P_t \):

\[
d(P,P_t) = \sqrt{(x-x_d)^2 + (y-y_d)^2 + (z-z_d)^2}.
\]

Then, we calculate the modulation matrix using the following equation:

\[
M_w = I - \frac{n_w n_w^T}{\mathbf{\Gamma}_w \rho_w n_w^T n_w}
\]

(5)

where \( \omega_w \) is the weighting coefficient, and \( \omega_w = \prod_{j=1}^w \frac{1}{(\Gamma_j - 1) + (\mathbf{\Gamma}_w - 1)} \) if \( W = 1 \); \( \mathbf{\Gamma}_w \) is the normal vector, and \( n_w = [\frac{\partial \mathbf{\Gamma}_w}{\partial x}, \frac{\partial \mathbf{\Gamma}_w}{\partial y}, \frac{\partial \mathbf{\Gamma}_w}{\partial z}]^T \).

The disturbed fluid velocity is

\[
\vec{u} = \tilde{M}(\mathbf{u} - v) + v
\]

(6)

Finally, the next waypoint can be calculated by the following equation.

\[
P_{k+1} = P_k + \vec{u} \cdot \Delta T
\]

(7)
where $\Delta T$ is the iteration time step. Eventually we can obtain all the re-planned waypoints, forming the re-planned route that can successfully avoid the intruder and reach the position of destination.

The flow chart of IFDS is shown in Fig. 1.

The experiments are executed in MATLAB R2011a on the computer with Intel Core i5 CPU processor and 2.5GHz frequency. The necessary parameters are: The minimum safe distance is $D_L = 50m$; UAV speed is $V_a = 60m/s$; Intruder speed is $V_m = 120m/s$; UAV speed direction is $\phi_a(0) = 0$; Maximum UAV turn rate is $\omega_{max} = 15^\circ/s$; Intruder speed direction is $\phi_m = 240^\circ$.

Based on the above simulation condition, we calculate the proposed regions. Fig 2 shows no-maneuver collision region in 2D and 3D. Fig 3 illustrates the maximum maneuverability collision region (left- and right-turning). Fig 4 shows safe flight envelope in 2D and 3D. And then the result of re-planning path by the IFDS algorithm and the proposed collision region is shown in the Fig 5. The simulation results demonstrate that the re-planned flight path can avoid obstacle smoothly and reach the destination eventually.

All the results show that the presented collision regions are useful for UAV to detect collision and select avoidance maneuver. And the simulation results also demonstrate the effectiveness of the presented flight path re-plan method.
Conclusion
This paper proposed a UAV collision detection, collision decision and path re-planning method. Firstly, models of UAV 3D dynamic collision regions were presented. Then the proposed 3D collision regions were used to detect collision. Further, an appropriate collision decision method was proposed based on the proposed regions and interfered fluid dynamical (IFDS) algorithm. And the IFDS algorithm was introduced to re-plan UAV’s flight path. Finally, simulation results demonstrate the effectiveness of this method.

Acknowledgement
This research was financially supported by the National Natural Science Foundation of China (No. 61175084), Program for Changjiang Scholars and Innovative Research Team in University (No. IRT13004).
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