Research Article

Autonomous Anticollision Decision and Control Method of UAV Based on the Optimization Theory

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Autonomous anticollision of unmanned aerial vehicle (UAV) is one of the key technologies to realize intelligent decision-making and autonomous control, and it is of great significance to improve the flight safety and survivability of UAV in complex environment. Firstly, the UAV autonomous anticollision system configuration is constructed in this paper, and the UAV autonomous anticollision problem and related models are described. Then, the potential collision conflict prediction rules are defined, and a practical three-dimensional collision conflict prediction method is proposed. Finally, the UAV autonomous avoidance decision-making method is designed by using the optimization theory, and the corresponding simple and feasible flight control law is put forward. Numerical simulation results show that the proposed method can ensure the flight safety of UAV by relying on autonomous decision-making and control strategy, so as to realize the autonomous anticollision between a single UAV and non-cooperative dynamic obstacles in three-dimensional airspace.

1. Introduction

With the rapid development of aviation industry in various countries, UAVs have been widely used in war and civil fields, resulting in a sharp increase in the number of various combat aircraft, including UAVs, which also leads to an increasing flight density and severe flight safety situation [1, 2]. Therefore, UAV autonomous anticollision technology is one of the key technologies of UAV autonomous control technology, which is of great significance to improve the survivability of UAV in complex environment. Especially for non-cooperative dynamic obstacles, UAV autonomous anticollision system has become an urgent need [3, 4].

The research of UAV anticollision has attracted great attention of scholars at home and abroad. In terms of intelligent solution algorithm, literature [5, 6] studies genetic avoidance algorithm, adopts discrete waypoint model, and considers the error caused by aircraft speed uncertainty. This method is easy to expand to three-dimensional without increasing complexity, but the accuracy needs to be strengthened. In terms of graph theory, literature [7, 8] analyzes the complexity of multi aircraft flight collision and uses the method of establishing a Voronoi polygon to solve the anticollision problem, but it is only applicable to two-dimensional plane. Literature [9–12] uses the artificial potential field method to treat UAV and obstacles as positively and negatively charged particles respectively, so as to construct a cooperative anticollision method, but this method cannot effectively solve the anticollision problem with constraints. In solving the multi constraint anticollision problem, the model predictive control method has a good effect [13]. References [14, 15] established an anticollision control algorithm under nonlinear constraints in two-dimensional environment by comprehensively using geometric method and model predictive control method and based on the tangent principle. Literature [16] proposed a multi UAV cooperative anticollision method under nonlinear dynamic constraints by using distributed model predictive control, but the premise of this method is that all obstacles are cooperative and their states are accurately known.
Through the above analysis, it can be found that the current research on UAV anticollision mainly has the following problems: (1) most of them are aimed at cooperative obstacles, which is difficult to meet the requirements of non-cooperative anticollision and has great limitations. (2) Many methods do not consider the dynamic constraints of UAV, which is inconsistent with the actual situation. (3) The computational complexity of model predictive control method is high, which is difficult to meet the real-time requirements of the system.

Therefore, based on the optimization theory, this paper studies the autonomous anticollision control method of UAV for non-cooperative dynamic obstacles. Firstly, the dynamic obstacle autonomous anticollision problem is reasonably described, which is divided into two parts: collision prediction and autonomous avoidance. Then a three-dimensional dynamic collision prediction algorithm is proposed. On this basis, the UAV autonomous anticollision control strategy is designed. Finally, the correctness and effectiveness of the proposed method are verified by simulation experiments.

2. Preliminaries and Problem Statement

2.1. UAV Autonomous Anti-Collision System. The UAV autonomous anticollision system for non-cooperative dynamic obstacles is shown in Figure 1.

UAV detects the obstacles that may be encountered in the flight process through airborne sensors and other equipment to realize the perception of the surrounding environment. Then, based on certain rules, the collision conflict is predicted. If the collision is predicted, the autonomous anticollision strategy is started. Among them, the autonomous anticollision strategy mainly includes three parts: anticollision guidance, emergency anticollision and pre planning tracking. Its output has two forms: waypoint and maneuver command. After collision avoidance, the UAV returns to the preset route. If it does not happen, the UAV will fly normally along the preset route.

2.2. Description of UAV Autonomous Anti-Collision Problem.

UAV status information is represented by an identifier, a position and a speed vector. The identifier is assumed to be unique and unchanged. That is, there will not be two different UAVs with the same identifier in the same airspace. Letters are used to represent UAV status, and bold letters represent vector parameters. For example, \( S \) represents position vector and \( V \) represents speed vector. When a vector variable represents a UAV, the UAV state is taken as the footmark: for example, the current position and speed vector of a UAV \( A \) are represented by \( S_A \) and \( V_A \), respectively. Generally, the angle dividing mark \( x, y, z \) represents the value on each direction axis. For example, \( V_{A}^{x}, V_{A}^{y} \) is the horizontal component of velocity \( V_A \), and \( S_A = [S_A^{x}, S_A^{y}, S_A^{z}] \).

It is assumed that the autonomous sensing function in the function of UAV autonomous anticollision system has been realized, the initial position and speed information is accurate, and the radius, position and speed vector of the intruder can be obtained. At the same time, the dynamic obstacles are represented by the sphere protection area in the coordinate system. The reserve defines a minimum safety interval between two machines, that is, a sphere with a diameter of \( D \).

In order to study the anticollision methods of UAV against dynamic obstacles, a set of basic concepts for collision prediction and avoidance methods of all dynamic obstacles are defined, and then the related research of this paper is carried out on this basis.

**Definition 1** (Protected area). The protected area of UAV \( A \) is defined as a point set \( P_A \), which meets the following requirements:

\[
P_A = \left\{ X \mid ||S_A - X|| < \frac{1}{2} \right\},
\]

where, \( X \) is the position of any point in space, \( || \cdot || \) is a vector norm, so that \( Y \) also represents the position of a point in space, satisfying:

1. Non-negativity: \( ||X|| \geq 0 \),
2. Zero value: \( ||X|| = 0 \) if and only if \( X = 0 \),
3. Homogeneity: \( ||kX|| = |k||X|| \),
4. Trigonometric inequality: \( ||X + Y|| \leq ||X|| + ||Y|| \).

The above is the abstract concept of all protected areas. In this paper, the imaginary protection area around each UAV is a sphere with a diameter of \( D \), that is, the sphere protection area of UAV \( A \) is defined as a point set \( P_A \) satisfying:

\[
\sqrt{(x - S_{Ax})^2 + (y - S_{Ay})^2 + (z - S_{Az})^2} < \frac{D}{2}
\]

Therefore, its norm is defined as:

\[
\| (x, y, z) \| = \frac{\sqrt{x^2 + y^2 + z^2}}{D}
\]

**Proposition 1.** Equation (3) is a normal norm vector, which satisfies non-negativity, zero value, homogeneity and triangular inequality.

Proposition 1 makes the definition of the loss of distance and safety interval between UAVs independent of the choice of the shape of the protected area.

**Definition 2** (Distance). The distance between UAV \( A \) and \( B \) is defined as:

\[
\Delta (A, B) = ||S_A - S_B||.
\]

**Definition 3** (Loss of safety interval). The loss of safety interval between UAVs is when the protection areas of two UAVs overlap, that is:

\[
P_A \cap P_B \neq \varnothing.
\]
**Proposition 2.** UAV A and B safety interval are lost if and only if:

\[ \Delta(A, B) < 1. \]  \hspace{1cm} (6)

**Definition 4 (Collision conflict).** The collision conflict between UAV A and B is that if there is a future time before exceeding time T, that is, when \( 0 \leq t < T \), the distance between the two aircraft is strictly less than 1.

\[ \Delta(A(\tau), B(\tau)) < 1. \]  \hspace{1cm} (7)

Collision is usually determined by comparing the predicted closest interval between two unmanned aircraft with the minimum safety interval defined by the protected area.

**Definition 5 (Closest interval).** The closest interval between UAV A and B in the override time T is \( \tau_T(A, B) \), i.e. the minimum time \( \tau \) \( (0 \leq \tau < T) \), which is different for any time \( t \) of \( 0 \leq t < T \):

\[ \Delta(A(\tau), B(\tau)) < \Delta(A(t), B(t)). \]  \hspace{1cm} (8)

The closest interval always exists because \( \Delta \) is a continuous function and the time range \( 0 \leq t < T \) is defined as a closed interval.

**Definition 6 (Closest interval distance).** The closest interval distance between UAV A and B within the override time T is the distance between two UAVs at the closest interval time, i.e:

\[ \delta_T(A, B) = \Delta(A(\tau_T(A, B)), B(\tau_T(B, A))). \]  \hspace{1cm} (9)

Therefore, the collision conflict based on the closest interval distance can be redefined.

**Proposition 3.** UAV A and B have collision conflict if and only if \( \delta_T(A, B) < 1. \)

**Definition 7 (Evasion strategy).** The evasion strategy \( R_A \) is that the UAV A only modifies the new state of the current speed vector. The new speed of UAV A under \( R_A \) is expressed as \( V_{RA} \).

Avoidance strategies can be classified according to the interval criteria they meet. Let \( R_A \) and \( R_B \) be the avoidance strategies of UAV A and B respectively:

1. When \( \delta_T(R_A, B) \geq 1, R_A \) is a non-cooperative evasion strategy for UAV A (UAV B does not maneuver), if \( \delta_T(R_A, B) = 1, R_A \) is also a tangent evasion strategy.
2. When \( \delta_T(R_A, R_B) \geq 1, R_A \) and \( R_B \) is the cooperative avoidance strategy, if \( \delta_T(R_A, R_B) = 1, R_A \) and \( R_B \) is also the smallest avoidance strategy.
3. When \( \delta_T(R_A, R_B) > \delta_T(A, B), R_A \) and \( R_B \) are mutually exclusive avoidance strategies.

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**Figure 1:** Anticollision system configuration of UAV.
The anticollision of UAV against dynamic obstacles can be clearly divided into three stages: the first stage is the state estimation of intruder. The second stage is conflict prediction. The potential conflict between the two aircraft will be predicted and whether the minimum interval loss will occur in their future position after a period of time (i.e. whether the UAV \( O \) enters the UAV \( I \) protection area). Once the conflict situation is predicted, it will enter the third stage, that is, the UAV loaded with autonomous anticollision function will take corresponding avoidance methods in time. The state estimation can adopt the similar extended Kalman filter method to obtain the estimated state of the intruder \([17]\). This section assumes to study the collision prediction and avoidance method of dynamic obstacles when the state of the intruder has been obtained.

### 3. Dynamic Obstacle Collision Prediction Rules

#### 3.1 Two-Dimensional Dynamic Collision Conflict Prediction

Based on the basic definition of the protected area, a protected area centered on the intruder coordinate system is considered, that is, a circle with diameter \( D \). The loss of safety interval occurs at time \( t \), and only if the projection distance between the two machines at time \( t \) is strictly less than \( R \) (i.e. \( D/2 \)). Assuming that \( S_0, V_0 \) and \( S_1, V_1 \) are the position and ground velocity vectors of the local machine and the intruder at time 0, there is:

\[
| (S_0 - S_1) + t(V_0 - V_1) |^2 < R^2.
\]

Time \( t \) has a solution if and only if:

\[
| (S_0 - S_1) + t(V_0 - V_1) |^2 = R^2.
\]

There are two solutions \( t_1, t_2 \), which meets \( t_1 \neq t_2 \). Two solutions are the start and end time of the security interval loss. By definition, if \( t_1 = t_2 \), no interval loss occurs. This two-dimensional method was proposed and applied by Bilimoria \([18]\). The intruder is considered to be fixed in space, and the local position \( S \) and speed \( V \) adopt the quantity relative to the state of the intruder, i.e. \( S = S_0 - S_t \) and \( V = V_0 - V_t \). If a new relative speed of the local machine can make it disjoint with the inside of the intruder protection zone, the collision can be avoided. Among the infinite new velocity vector solutions to avoid collision, Bilimoria selects the velocity vector with the smallest angle with its original velocity vector as the optimal solution. As shown in Figure 2, any other solution requires a large number of changes to the ground path of the local machine, so any optimal solution is tangent to the intrusion machine protection zone. A new local path to the ground is determined every time it passes through points \( A \) and \( B \). Under certain constraints, it is optimal. For example, the constraint condition is that it can only turn left, and the target point \( A \) is optimal. The length of the velocity vector is optional.

Bilimoria two-dimensional method can predict and avoid horizontal conflicts, but it does not consider vertical conflicts. In reference \([19]\), the three-dimensional conflict is decomposed into horizontal and vertical conflicts, so that the collision conflict can be predicted and avoided independently, and then the solutions in all directions are combined to obtain three-dimensional maneuver. Although this method is simple, it is difficult to prove its correctness. Based on Bilimoria’s two-dimensional horizontal conflict prediction and avoidance method, a real three-dimensional collision prediction and avoidance method for dynamic obstacles is proposed.

#### 3.2 Collision Prediction Rules for 3D Dynamic Obstacles

Based on the two-dimensional dynamic obstacle collision prediction rules, a new three-dimensional dynamic obstacle collision prediction rule is proposed to realize three-dimensional collision prediction. Assuming that \( O \) and \( I \) represent UAV and intrusion UAV respectively, and the intrusion UAV is a non-cooperative obstacle, the autonomous anticollision problem studied in this paper can be regarded as that the UAV \( O \) first predicts the collision conflict with the intrusion UAV \( I \), and then adopts the autonomous anticollision strategy to complete anticollision. The flight diagram of the two is shown in Figure 3.

Assuming that \( \delta \) is the smallest possible interval between \( O \) and \( I \), after a certain period of time, the expression of \( \delta \) becomes:

\[
\delta = \frac{S \cdot V}{||V||} - V - S.
\]

**Theorem 1.** Both UAV \( O \) and intruder UAV \( I \) (a sphere with radius \( R \)) fly at a constant speed, and the speed is \( V_0 \) and \( V_I \) respectively. The two UAVs collide, if and only if the following formula is true:

\[
||\delta|| \leq R, \dot{S} < 0,
\]

where, \( W = ||S|| \).

**Proof.** Let \( \pi \) be the plane of vectors \( V \) and \( S \). The plane intersects the sphere \( I \) to determine a circle \( C \) with radius \( R \), as shown in Figure 3. In Figure 4, also considering this plane, the particle \( O \) collides with the sphere \( I \) with radius \( R \) if and only if the particle \( O \) is assumed to collide with the assumed stationary circle \( C \) in plane \( \pi \) at constant velocity \( V \). Considering the right unit vectors \( S \) and \( S^* \), the following expression can be obtained:
The condition \( V_S = W < 0 \) indicates that the UAV is approaching. In order to prove (13), first prove the following equivalent equation:

\[
\|\delta\| \leq R \Rightarrow W^2V_\theta^2 \leq R^2\left(\frac{V_S^2}{V_\theta^2} + \frac{V_\theta^2}{V_S^2}\right).
\]

(16)

And because \( S = WS, V = V_S\overline{S} + V_\theta\overline{S}_\parallel \Rightarrow S \cdot V = W V_S \), we have:

\[
\delta = \frac{W V_S}{(V_S^2 + V_\theta^2)}\left(V_S\overline{S} + V_\theta\overline{S}_\parallel\right) - W\overline{S} = -\frac{W V_\theta^2}{(V_S^2 + V_\theta^2)}\overline{S} + \frac{W V_S V_\theta}{(V_S^2 + V_\theta^2)}\overline{S}_\parallel
\]

(17)

\[
\|\delta\| = \frac{S^2 V_\theta^2}{V_S^2 + V_\theta^2}
\]

4. Autonomous anticolliision strategy based on optimization

Figure 5 shows the geometric diagram describing the anticollision between two non-cooperative UAVs in the threedimensional inertial reference coordinate system. It is assumed that the UAV model equipped with airborne autonomous anticollision system is represented by a particle \( O \) with velocity \( V_O \), while the other intruder \( I \) is assumed to be a sphere with a half diameter \( R \) of the protected area and a velocity of \( V_I \).

Then the UAV autonomous anticollision strategy for non-cooperative dynamic obstacles can be described as the following optimization problem: Find the solution that enables the UAV \( O \) to independently avoid the invading UAV \( I \) and minimize the deviation from the preset route.

The UAV \( O \) position vector is expressed as: \( S_O(t) = [x_O(t), y_O(t), z_O(t)]^T \), and the intruder UAV \( I \) position vector is expressed as: \( S_I(t) = [x_I(t), y_I(t), z_I(t)]^T \). \( S_O(t) \) can be calculated from \( V_O(t) \) by:

\[
S_O(t) = S_O(t_0) + \int_{t_0}^{t} V_O(\tau) d\tau.
\]

(18)

Assuming that \( S^d_O(t) \) is the position vector calculated according to the desired speed \( V^d_O(t) \), the deviation value is:

\[
S^d_O(t) - S_O(t) = \int_{t_0}^{t} [V^d_O(\tau) - V_O(\tau)] d\tau.
\]

(19)

The goal is to minimize the deviation value under the constraints of UAV itself. The problem is expressed as follows:

\[
\begin{align*}
\min_{V_O(t), S_O(t)} & \int_{t_0}^{t} \Delta V_O(\tau) d\tau \\
\text{s.t.} & \left\|S^d_O(t) - S_I(t)\right\| \geq R, \quad \forall t \geq t_0 \\
& V_O(t) \in [V_{O_{\min}}, V_{O_{\max}}], \\
& \phi_O(t) \in [\phi_{O_{\min}}, \phi_{O_{\max}}] \\
& \exists \theta_O > 0
\end{align*}
\]

(20)

where, \( \|S^d_O(t) - S_I(t)\| = \|S(t) + \int_{t_0}^{t} \Delta V_O(\tau) d\tau\| \geq R \), which represents the collision prevention between UAV \( O \) and
Intrusion using the analytical method, the above problem can be determined a vector
\[ V_{O} \parallel V(t_0) + \Delta V_{O}(t_0)(t - t_0). \] (21)

The first constraint is:
\[ \|S(t) + \Delta V_{O}(t_0)(t - t_0)\| \geq R, \quad \forall t \geq t_0. \] (22)

Meanwhile, we have: \( \Delta V_{O} = V_{d} - \Delta V_{O} = (V_{d} - V_{I}) - (V_{O} - V_{I}) = V_{d} - V \) and \( S(t) = S(t_0) + V(t - t_0) \).

Then equation (22) continues to be:
\[ \|S(t) + V_{d}(t - t_0)\| \geq R, \quad \forall t \geq t_0. \] (23)

It can be proved that \( t = t^* \equiv S(t_0) \cdot V_{d}/\|V_{d}\|^{2}, \|S(t_0) + V_{d}(t - t_0)\| \) is the smallest, and the result is \( \|\delta_{d}\| \). Since \( \|\delta_{d}\| \equiv R \) (tangent to the reserve), equation (22) is satisfied. At this point, equation (20) becomes:
\[
\begin{align*}
\text{min} & \quad \|\Delta V_{O}\|, \\
\text{s.t.} & \quad \|\delta_{d}\| = R.
\end{align*}
\] (24)

An analytical solution can be obtained for this new problem, which is proved in the form of geometric description as follows.

It is necessary to find the minimum \( \Delta V_{O} \) and apply it to the velocity vector \( V_{O} \) so that the new velocity vector \( V_{O}' = V_{O} + \Delta V_{O} \) is tangent to the protected area. The unit vector of \( V_{d} \) is expressed as \( \hat{V}_{d} \). In the plane constructed by the unit vectors \( \hat{V} \) and \( \hat{V}_{d} \), minimizing \( \Delta V_{O} \) can be applied to the orthogonal projection of \( \hat{V} \) on \( \hat{V}_{d} \) : the modulus of any vector \( \Delta V_{O} \) is greater than \( \Delta V_{O} \), as is shown in Figure 6. Then, \( \|\Delta V_{O}\| = \|V\|\sin \Omega \), \( \Omega \in [0, \pi/2) \).

In order to find the minimum value of \( \Delta V_{O} \), first solve \( \hat{V}_{d} \), which is tangent to the reserve and expressed by the minimum angle \( \Omega \). Therefore, circle \( C_{\Omega} \) is the intersection of the cone with angle \( \Omega = \sin^{-1}R/\|S\| \) to the \( S \)-axis and the protected area, as shown in Figure 7.

For any point \( C \) on circle \( I' \), as is shown in Figure 8, \( O\hat{C} \) determines a vector \( \hat{V}_{d} \) tangent to the reserve. However, \( C^* \) on \( \pi \) is the only point to ensure the minimum of \( \Omega \) (i.e. the minimum of \( \Delta V_{O} \)). Because \( \Delta \) the analytical expression of \( V_{d} \) must be found in plane \( \pi \).

If angles \( \eta \) and \( \xi \) have the same sign, then \( \Omega = \eta - \xi \) is the smallest. It is divided into the following two cases: \( \xi \neq 0 \) and \( \xi = 0 \).

1. \( \xi \neq 0 \) (General) The minimization form \( V_{d} \) of \( \Delta V_{O} \) can be obtained from Figure 9 by
\[
\begin{align*}
V_{d} &= V_{d}' - V_{I} = V_{d}' \sin \theta \hat{S} + V_{d}' \cos \theta \hat{S}, \\
\hat{V}_{d} &= \frac{V \cos (\eta - \xi)}{\sin \xi} \sin \theta [\sin \eta \cdot \hat{V} - \sin (\eta - \xi) \cdot \hat{S}].
\end{align*}
\] (25)

Equation (25) is the global optimal solution of general problem (20) under assumptions

2. \( \xi = 0 \) (Special) This unity depends on the relationship between \( V \) and \( S \). At this time, plane \( \pi \) is not defined singly, but must be selected from a group of plane bundles in the same direction as \( S \).
4.1. Design Principle of Reserve. In order to consider the dynamic constraints, the radius $R$ of the reserve can be expanded. In this paper, the expanded reserve is selected as $R' = R + \Delta R$, where $R = 500\text{ft} = 152.4\text{m}$ (according to the American FAA accident standard), $\Delta R$ can be designed as a conservative estimate of all possible maneuvers that the intruder can perform in time $t_d'$. $\Delta R = t_d' \cdot V_{\text{MAX}}$. If $I$ and $O$ have the same performance, such as $t_d' = 10\text{s}$ and $V_{\text{MAX}} \approx 45\text{m/s}$, even if $I$ is a pursuer, $R' = R + \Delta R = 4R = 2000\text{ft}$ and the protection area with radius $R' = 4R$ is enough to ensure anticollision (the relative distance between the two aircraft is always greater than $R = 500\text{ft}$).

Because the radius of the reserve $R' = R + \Delta R$ is properly designed with $\Delta R$, if $I$ and $O$ have the same performance, it can ensure that the minimum distance between the two aircraft is always greater than $R$, and even if $I$ is the pursuer, the initial relative distance is greater than a critical distance. However, in some cases, $O$ still enters the reserve with radius $R'$. In this case, the tangent solution (25) cannot be used because there is no tangent passing through a point in the sphere and tangent to the sphere with radius $R'$.

Therefore, when $O$ is located in the protection zone with radius $R'$, another strategy can be selected: in this case, the speed vector $V_{Od}$ required for the UAV $O$ autopilot is defined as shown in Figure 10. The adopted strategy provides a powerful control maneuver to quickly move the UAV out of the protected area with radius $R'$, and then continue to apply the tangent solution (25).

### 4.2. Anti-collision Control Command under UAV Dynamic Constraints.

It is assumed that the current speed direction of the UAV is the direction of $V$ and the modified anticollision speed direction is the direction of $V_d$. Let $\phi$ be the roll angle of the UAV and $\theta$ be the pitch angle of the UAV, then equations (26) and (27) are the anti-anticollision guidance control commands generated under the boundary constraints of the UAV:

$$\phi = \frac{1}{N} (\phi_{\text{com}} - \phi),$$  \hspace{1cm} (26)

$$\dot{\theta} = \frac{1}{M} (\theta_{\text{com}} - \theta),$$  \hspace{1cm} (27)

where, $N, M$ is the UAV maneuver time delay constant. During the simulation, make $N = M = 1\text{s}$.

1. **Horizontal Maneuver**

In the horizontal plane, the line of sight inclination angle of the UAV is:

$$\lambda = \text{signum} \left( \left( \frac{V_{H} \times V_{d}^{H}}{|V_{H}|} \right) \right) \arccos \left( \frac{V_{H} \times V_{d}^{H}}{|V_{H}|} \right),$$ \hspace{1cm} (28)

where, $V_{H}$ is the horizontal component of velocity. Therefore, the roll angle of UAV is regarded as input. Make the maximum roll angle $\phi_{\text{max}}$, so that the maximum longitudinal inclination changes in 1 second:

$$y_{\text{max}} = \frac{g}{|V_{H}|},$$ \hspace{1cm} (29)

(for 1 second $\phi_{\text{max}}$).

The horizontal maneuver logic is shown in Table 1.

2. **Vertical Maneuver**

The desired pitch angle $\theta_{\text{req}}$ can be expressed as:

$$\theta_{\text{req}} = \arctan \left( \frac{V_{d}^{V}}{|V_{d}^{H}|} \right).$$ \hspace{1cm} (30)

The vertical maneuver logic is shown in Table 2.

### 5. Simulation and Analysis

It is assumed that the initial position, speed and target position information of two UAVs (UAV1 and UAV2) are shown in Table 3, where UAV2 is our UAV and UAV1 is a non-cooperative obstacle. During the flight, it is predicted that the two opportunities will collide, UAV2 will take

**Figure 10: Escape path with radius of protection zone being $R'$.**
corresponding evasion maneuver, and UAV1 will fly in a straight line. The obtained simulation curve is shown in Figures 11(a)–11(d).

From the simulation results, Figure 11(a) shows the flight trajectory of the two aircraft. The flight routes of UAV1 and UAV2 do not intersect. The dotted line in Figure 11(b) represents the ideal anticollision interval, and the solid line represents the real-time interval during the actual flight of the two aircraft. It can be seen that UAV2 has completed the autonomous anticollision with UAV1. Figure 11(c) shows the UAV2 roll angle command, and Figure 11(d) shows the UAV2 pitch angle speed command, both of which are within the limit range.

The obtained simulation curve is shown in Figures 11(a)–11(d).

To make a Monte Carlo simulation with 500 times, we find that the average running time of the method proposed in the paper is 20 ms, which has a great advantage on the existed anticollision method, such as the MPC algorithm in Ref. [13].

Therefore, the simulation results show that the proposed method can ensure the autonomous anticollision between UAV and non-cooperative obstacles.

6. Conclusions

Aiming at the non-cooperative anticollision problem in three-dimensional airspace, this paper studies the
autonomous anticollision decision and control method of UAV based on optimization theory. The autonomous anticollision problem of UAV is described and divided into two stages: prediction and avoidance, which provides a model basis for decision-making and control design. Based on the two-dimensional dynamic collision conflict prediction, a three-dimensional collision conflict prediction method is proposed to predict the collision between aircraft and effectively realize the environmental airspace cognition. By using the optimization theory, the autonomous anticollision decision and control method of UAV is designed. The simulation results show that the proposed method is effective in the three-dimensional airspace non-cooperative anticollision problem, and can greatly improve the flight safety of UAV. The research makes a contribution to the autonomous anticollision domain, and results of this paper can be applied to the design of UAV decision and control system. The next research focus is on the cooperative anticollision decision and control of multi-UAVs or UAV cluster.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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