Autonomous evasion method for drones under static threat

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Abstract. In the flight area, it is difficult for drones to have a clear understanding of all threats in advance, that is, there are some sudden static threats, which requires real-time detection and avoidance of drones during flight. This paper proposes an improved RPG method for UAV threat evasion guidance control, and gives the UAV threat evasion guidance law.

1. Introduction

The traditional method to deal with sudden static threats encountered by drones during flight is online route replanning, that is, if the drone detects an unmarked threat source on the map through the onboard sensors, it uses its scheduled flight Whether the route intersects with the threatened protected area to determine the risk probability of the aircraft being hit. If they intersect, route re-planning is needed. A specific method for obtaining a safe route through route replanning is to change the curvature of a predetermined route between two waypoints or to add an intermediate waypoint between two predetermined waypoints and generate a new route passing through the waypoint.

2. Emergent Static Threat Avoidance

It is assumed that the height and speed of the drone remain unchanged during full flight, and that the conditions for coordinated turning are met when turning. If the drone requires tracking to a specified fixed target in the ground coordinate system. Since the location information of the fixed target is known, it is not difficult to track the fixed target point. It is also assumed that $X_{obs}$ is the position of the threat center in the ground coordinate system, and $\dot{X}_{obs} = 0$, that is, the threat source is stationary. To avoid the threat source, the drone must maintain a minimum safe distance $R$ from the threat source.

That is, the drone must meet:

$$d_{\text{min}} = \|X_{obs} - X_{\text{uav}}\|_{\text{min}} > R \quad (1)$$

In order to achieve security evasion of threats. Among them, $d_{\text{min}}$ is the closest distance between the drone and the threat center. When $d_{\text{min}} < R$, an unmanned opportunity enters the threat area, and an evasion action is required to fly around the safety boundary. At this time, the threat avoidance task is transformed into the tracking problem of the drone on the curved route. The RPG guidance law can be applied.
3. Threat State Estimate

In this paper, when an unmanned opportunity is encountered and an unexpected static threat is encountered, the on-board CCD camera is used for real-time detection. The CCD camera will project the three-dimensional information of the threat onto a two-dimensional image plane, which will cause non-linearity. Make estimates.

Extended Kalman filtering is used to estimate the relative position of the threat. Since the threat is assumed to be stationary, the dynamic equation of the threat is:

\[ \dot{X}_{\text{obs}}(t) = 0 \]  

(2)

Therefore, the extended Kalman filter of the formula can be written as:

\[ \hat{X}_k = \hat{X}_{\text{obs}} - X_{\text{uav}} \]

\[ P_k = P_{k-1} + Q_k \]  

(3)

In formula (3), \( X_{\text{uav}} \) is the known drone position, \( Q_k \) is the covariance matrix, \( \Delta t_k = t_k - t_{k-1} \) is the sampling time.

\[ \hat{X}_k = \hat{X}_k^- + K_k (Z_k - h(\hat{X}_k^-)) \]

\[ P_k = P_k^- - K_k H_k P_k^- \]

\[ K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \]  

(4)

In formula (4), \( h(\hat{X}_k^-) \) is shown in formula (5). The measurement matrix is:

\[
H_k = \frac{\partial h(\hat{X}_k^-)}{\partial \hat{X}_k^-} = \begin{bmatrix}
\dot{Y}_{\text{c}} \\
\dot{X}_{\text{c}} \\
\dot{Z}_{\text{c}}
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
X_{\text{c}} & 1 \\
\dot{X}_{\text{c}} & 0 & 1
\end{bmatrix} \quad T_{c_k} = \frac{1}{\hat{X}_{\text{c}}^-} [h(\hat{X}_k^-) - I] T_{c_k} \]  

(5)

After completing the EKF update, the absolute position of the threat is estimated as:

\[ \hat{X}_{\text{obs}} = \hat{X}_k + \hat{X}_{\text{uav}} \]  

(6)

4. Threat Protected Area Conflict Judgment Method

The two factors determining the threat protected area are the size and shape. Since this chapter assumes that the drone remains at the same height during full flight, the threat protected area degrades into a circle in a two-dimensional plane, so only the radius of the protected area needs to be determined. Just fine. Taking into account the dynamic constraints of the drone, that is, the closed-loop system "drone + autopilot" has a limited processing time for speed vector changes, set to \( t_0 \), which is the speed required for the drone to avoid sudden static threat. It cannot be reached instantaneously, so the radius of the protected area should be expanded. This article chooses to expand the protected area radius to \( R = R_0 + \Delta R_0 \), and \( \Delta R_0 \) can be designed as a conservative estimate of all possible
maneuvers that a drone can execute within time $t_0$: $\Delta R_0 = t_0 \cdot V_{\text{max}}$, $V_{\text{max}}$ is the maximum speed value of the drone during the processing time $t_0$.

When solving the problem of whether the drone invades the threat protection area, first set a threat protection area with a radius of $R$ around the threat center, which can determine the conflict between the drone and the threat area, that is, whether the two will remain constant. The question of separation distance translates into whether the movement of the drone will invade. Based on the conflict description of the two-dimensional static threat area, a conflict judgment is made between the UAV and the threat protection area in the ground coordinate system. As shown in Figure 1:

\[ d_{\text{min}} = \left| (y_M - y_f) \cos \varphi - (x_M - x_f) \sin \varphi \right| \]  

As can be seen from Figure 1, if $d_{\text{min}} < R$, it is determined that if the drone continues to fly along the long-distance route, it will invade the surrounding protection area, that is, the drone is considered to have a greater probability of being shot down, and an evasion action is required, otherwise the drone will not be shot down.

5. Method for avoiding sudden static threat based on RPG guidance

5.1. Basic theory of RPG guidance method

Fig. 2 shows the principle of applying the RPG (Reference Point Guidance) guidance method to make the UAV track the desired route.
The lateral acceleration required to drive the aircraft from the current point $O$ along the arc $OP$ to the reference point $P$ is:

$$a_c = \frac{V^2}{R}$$

(8)

The lateral acceleration in equation (8) can be written as:

$$a_c = \frac{2V^2}{L_1} \sin \eta$$

(9)

Again,

$$a_c = \phi^2 R = \phi^2 \frac{L_1}{2\sin \eta}$$

(10)

Substituting the expression of $a_c$ in formula (10) into formula (9), we get:

$$\phi = \frac{2V}{L_1} \sin \eta$$

(11)

5.2. Guidance law for drone threat avoidance based on RPG

It is known from the foregoing that the distance between the drone and the threat center should be greater than or equal to $R_0$. Therefore, a reference track with a radius of $R$ ($R \geq R_0$) is determined outside the threat area, and it is tracked by the RPG route tracking guidance control method, as shown in Figure 3. As shown, the intersections of the $L_1$ circle and the reference track are A and B respectively. Taking the situation shown in the figure as an example, drone maneuvering to the right is less expensive than maneuvering to the left, and the avoidance route deviates from the original route less Therefore, point A is selected as the reference point. $\gamma$ is the angle between the connection between the threat center and the drone relative to the current speed of the drone $V$, which is positive to the right of $V$. 
If the drone's turning angular rate changes according to the law in formula (11), the lateral acceleration command is converted into a rolling angle control command by the coordinated turning conditions, and we get:

$$\phi_{com} = -\text{sign}(\gamma) \arctan \frac{a_c}{g}$$

(12)

Substituting the expression of $a_c$ in formula (27) into the above formula, we get:

$$\phi_{com} = -\text{sign}(\gamma) \arctan \left( \frac{2V^2}{gL_1 \sin \eta} \right)$$

(13)

Formula (13) is the threat avoidance guidance law, where $g$ is the acceleration of gravity. In this paper, RPG guidance law is used for threat avoidance. The actual flight path of the generated UAV is the avoidance path. Therefore, RPG can not only be used for threat evasion, but also can control drones flying on airways, avoiding the hidden dangers caused by frequent switching of guidance control methods during flight.

6. Conclusion
This article focuses on the evasion of a single drone to a sudden static threat in the mission area. After estimating the location information of the threat, a method for determining whether the drone will invade the threat area is given, and the RPG is guided. The method is applied to avoiding such threats by UAVs, and then the timing and reference point selection of UAV evasion guidance are further given. Finally, by analyzing the change process of the relative distance between the UAV and the threat center, the feasibility of the method is theoretically proved and the method used is simulated and verified.

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