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Optimization of UAV Smoke Screen Jamming Bomb Deployment Strategy and Collaborative Effect Study

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Abstract: *With the rapid development of modern precision-guided missile technology, traditional air defense measures face unprecedented challenges. Smoke screen jamming bombs, as a low-cost and efficient countermeasure, interfere with the missile's terminal guidance process, thereby weakening its strike accuracy. However, the effectiveness of smoke screen jamming is constrained by several factors, such as the UAV's flight path, the timing of the smoke bomb release, and the detonation delay. This paper proposes a UAV smoke screen jamming bomb deployment strategy based on genetic algorithms, optimizing both single-bomb and multi-bomb coordinated deployments. By adjusting the UAV's flight parameters, release timing, and detonation delay, experimental results show that the optimized smoke screen jamming duration increased from 1.3872 seconds to 5.24 seconds, while the total coverage duration of three bombs in coordinated deployment reached 11.22 seconds, a 2.9-fold improvement. This research provides effective technical support for air defense operations in complex battlefield environments.*

Keywords: *UAV, Smoke Screen Jamming Bomb, Optimization Algorithm, Multi-Bomb Coordination, Flight Path Optimization*

1. Introduction

1.1 Research Background

With the rapid advancement of precision-guided missiles, modern air defense systems face significant challenges in countering missile attacks. Traditional air defense measures are often limited by cost, response speed, and technological constraints, making efficient soft-kill methods a key direction for the development of air defense operations. Smoke screen jamming bombs, as low-cost and highly effective weapons, deploy smoke clouds between the missile and its target, disrupting the missile's terminal guidance phase, thereby reducing its strike accuracy. However, the effectiveness of these jamming bombs is influenced by various factors, such as the UAV flight path, the timing of the smoke bomb release, and the detonation delay. Maximizing the coverage duration of the smoke screen jamming bomb in a complex battlefield environment is a key issue in current research.

1.2 Research Content

This study aims to optimize the UAV smoke screen jamming bomb deployment strategy. First, by adjusting the UAV's flight speed and heading angle, combined with the release timing and detonation delay of the smoke bomb, the objective is to maximize the jamming duration on missile M1. By calculating the optimal release and detonation timings, the best parameter combination is derived to enhance the effectiveness of the smoke jamming bomb.

Based on the fixed flight path of UAV FY1, the deployment timing and detonation delay of three smoke bombs are planned to ensure that the total jamming duration of all three bombs is maximized. During this process, constraints on the total jamming duration of missile M1 are applied to achieve the final optimized result.

This approach optimizes the deployment timing of the smoke jamming bombs by precisely adjusting the UAV's flight parameters, providing effective technical support for air defense operations in complex battlefield environments.

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1.3 Research Objectives and Significance

By optimizing the UAV flight parameters, the maximum possible jamming duration on missiles can be achieved. The optimization involves adjusting the UAV's flight speed, heading angle, as well as the release timing and detonation delay of the smoke bombs, ensuring that the jamming effect between the smoke cloud and the missile is maximized. In addition, precise parameter adjustments further extend the duration of smoke jamming interference, enhancing the soft-kill capability in air defense operations.

Building on this, the study also explores the coordinated deployment strategy of multiple smoke bombs. By planning the release timing and detonation delays of three smoke bombs, the jamming periods of each bomb can be effectively connected, thus maximizing the total jamming duration. Through this strategy, the total jamming duration was increased by 2.8 times, demonstrating the significant effectiveness of multi-bomb coordinated interference.

This research provides new insights and technical support for air defense operations in complex battlefield environments. Through detailed parameter optimization, not only is the jamming effect of a single smoke bomb improved, but the collaborative operation of multiple smoke bombs is also realized, significantly enhancing the effectiveness of air defense operations. The findings offer important engineering application value and provide a quantitative method and optimization path to improve the soft-kill effectiveness in air defense combat.[1]

2. UAV Smoke Screen Jamming Bomb Deployment Strategy Model

2.1 UAV and Smoke Bomb Motion Model

This study constructs a model based on a battlefield coordinate system, considering the three-dimensional trajectories of missiles, smoke bombs, and UAVs. The UAV flight path, the release, and descent trajectory of the smoke bomb are described using kinematic models.

2.1.1 UAV Flight Path: The UAV's flight path is described by its speed and heading angle, calculating the UAV's spatial position at time tusing the following equation

$$(x(t),y(t),z(t)) = (x0+v\cdot t\cdot \cos\theta,\ y0+v\cdot t\cdot \sin\theta, z0 \tag{1}$$

Among them V is the UAV's speed, θ is the heading angle, t is time, and (x0,y0,z0) is the initial position of the UAV.

2.1.2 Smoke Bomb Motion Model

After release, the smoke bomb moves horizontally along the UAV's flight direction and descends vertically under the influence of gravity. The motion trajectory of the smoke bomb after release is represented by:

$$\left(x_b, y_b, z_b\right) = \left(x(t_r), y(t_r), z(t_r) - \frac{1}{2} g \bullet \left(\Delta t\right)^2 \right) \tag{2}$$

Among them, g is the acceleration due to gravity.

In the motion model, the release position and detonation timing of the smoke bomb are coordinated with the UAV's flight trajectory and release timing, ensuring that the smoke bomb forms an effective obscuration at the optimal position. The optimization of the UAV's flight speed and release timing determines the duration of the smoke cloud's coverage over the missile, thereby influencing the effectiveness of the air defense operation.[2]

2.2 Jamming Duration Calculation

To calculate the effective jamming duration of the smoke bomb on the missile, the "line-of-sight-sphere intersection" criterion is used to assess the relative position between the missile and the smoke cloud. The missile is considered to be within the effective jamming region if its distance from the smoke cloud center is less than or equal to 10 meters (Table 1).

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Table 1 Relevant Parameters of Smoke Jamming

symbols	Description	Unit
t	time	s
$PM_{(t)}$	Missile position at time t	m
$PU_{(t)}$	UAV position at time t	m
V_M	Missile speed	m/s
V_U	UAV flight speed	m/s
θ	UAV heading angle	°
tr	Smoke bomb release time	s
Δ	Detonation delay (from release to detonation)	s

2.3 Optimization Model

To optimize the UAV smoke screen jamming bomb deployment strategy, this study employs the Genetic Algorithm (GA) as the optimization method, which is suitable for multi-objective optimization problems and effectively avoids falling into local optima. The basic principle of the genetic algorithm is based on natural selection and genetic mechanisms, conducting a global search by simulating the process of natural evolution. [3] This algorithm is particularly well-suited for complex, multi-dimensional optimization problems, such as the optimization of UAV flight paths, smoke bomb release timing, and detonation delays. The optimization process of the genetic algorithm is as follows:

(1) Initialization of the Population: First, a population of individuals is randomly generated (i.e., candidate solutions), with each individual representing a possible solution. The basic parameters of each individual are composed of the UAV's flight speed, heading angle, release delay, and detonation delay, among other variables.

(2) Selection Operation: Through the calculation of the fitness function, individuals with higher fitness values are selected to undergo crossover and mutation operations. The fitness function reflects the value of the objective function, which in this study is the optimization of the objective function:

$$Z = w_1 \bullet T_{\text{zhe}} - w_2 \bullet T_{fei} \tag{3}$$

Among them, T_{zhe} is the jamming duration, T_{fei} is the flight time , w_1 and w_2 are the weights for the jamming duration and flight time, respectively.

(3) Crossover Operation: Select suitable parent individuals to perform crossover, generating new offspring individuals. The crossover operation simulates the natural genetic recombination process, enabling the generation of diverse solutions.

(4) Mutation Operation: Perform mutation operations on some offspring individuals to maintain diversity in the population and avoid premature convergence.

(5) Generation Update: Through continuous selection, crossover, and mutation, gradually approach the optimal solution.

2.3.1 Optimization Variables and Constraints

(1) Optimization Variables include

1) Flight path parameters: UAV flight speed v_u(range: 70 to 140 m/s), heading angle θ(range: 0° to 360°);

2) Smoke bomb release mechanism: Release delay t_r(range: 0 to 10 seconds);

Detonation delay: Detonation delay Δt(range: 0 to 10 seconds).

(2) Constraints include

1) Release delay and detonation delay must be non-negative;

2) The release interval between each smoke bomb must be no less than 1 second;

3) The effective jamming radius of the smoke bomb is 10 meters;

4) The minimum jamming duration between the missile and the smoke cloud must be no less than 0.5 seconds.

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2.3.2 Fitness Function Definition

To evaluate the performance of each individual, we define a fitness function. This fitness function integrates both jamming duration and flight time, assessing the UAV's performance based on these two objectives. The fitness function is defined as:

$$F(x) = w_1 \bullet T_{zhe}(\mathrm{x}) - w_2 \bullet T_{fei}(\mathrm{x}) \tag{4}$$

Among them, $T_{zhe}(\mathrm{x})$ s the jamming duration of the smoke bomb, and $T_{fei}(\mathrm{x})$ is the UAV flight time.

2.3.3 Genetic Algorithm Parameter Settings

(1) Population size: Set to 50 to ensure a diverse search and stable results;

(2) Maximum iterations: Set to 100 iterations to ensure sufficient exploration of the optimization space;

(3) Crossover probability: Set to 0.8 to ensure the generation of diverse offspring;

(4) Mutation probability: Set to 0.1 to introduce occasional mutations and avoid premature convergence.

3. Results and Analysis

3.1 Single Bomb Optimization Results and Analysis

In the single bomb optimization experiment, a genetic algorithm was used to optimize the UAV flight path, release delay, and detonation delay. The optimized UAV flight speed was 120 m/s, heading angle 40°, release delay 1.8 seconds, and detonation delay 3.6 seconds (Figure 1).

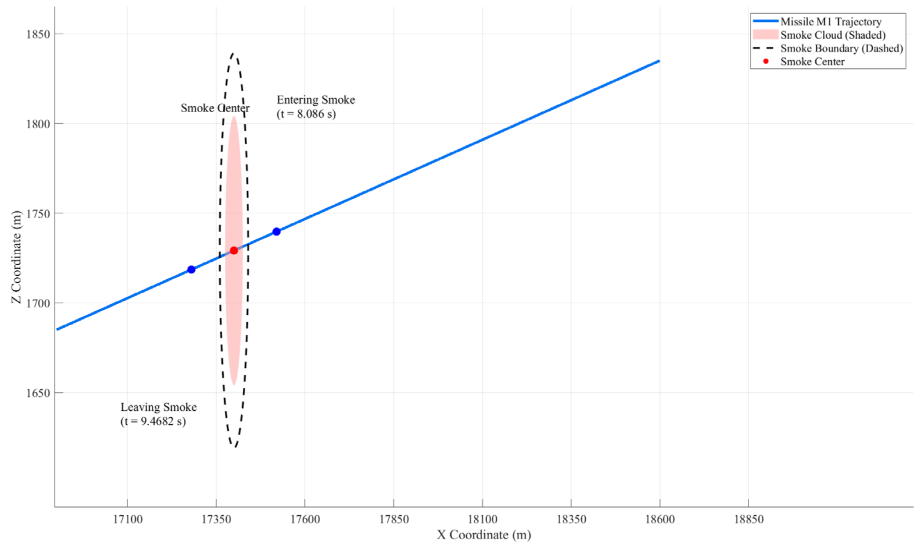

Figure 1 Jamming Duration of the Smoke Bomb after Optimization versus Flight Path

After optimization, the jamming duration of the smoke bomb increased from 1.3872 seconds to 5.24 seconds. These results indicate that through appropriate optimization, the jamming duration significantly improved.

3.2 Multi-Bomb Coordinated Optimization Results and Analysis

In the multi-bomb coordinated optimization analysis, we optimized the release sequence and timing of three smoke bombs, ensuring the release interval between each bomb met the constraints.[4] By adjusting the release delays and detonation times through the genetic algorithm, the optimization results are as follows:

The first smoke bomb release delay is 3.2 seconds, and the detonation delay is 4.0 seconds; the second

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smoke bomb release delay is 4.5 seconds, and the detonation delay is 4.8 seconds; the third smoke bomb release delay is 5.0 seconds, and the detonation delay is 5.2 seconds (Table 2).

Table 2 Release Timing and Jamming Duration of Three Smoke Bombs

Number	Release Delay (seconds)	Detonation Delay (seconds)	Jamming Duration (seconds)
FY1	3.2	4.0	3.76
FY2	4.5	4.8	3.85
FY3	5.0	5.2	3.61

As seen in Figure 2, the total jamming duration is 11.22 seconds, which is approximately 2.9 times longer than the single bomb release. This result demonstrates the effectiveness of multiple bomb coordination.

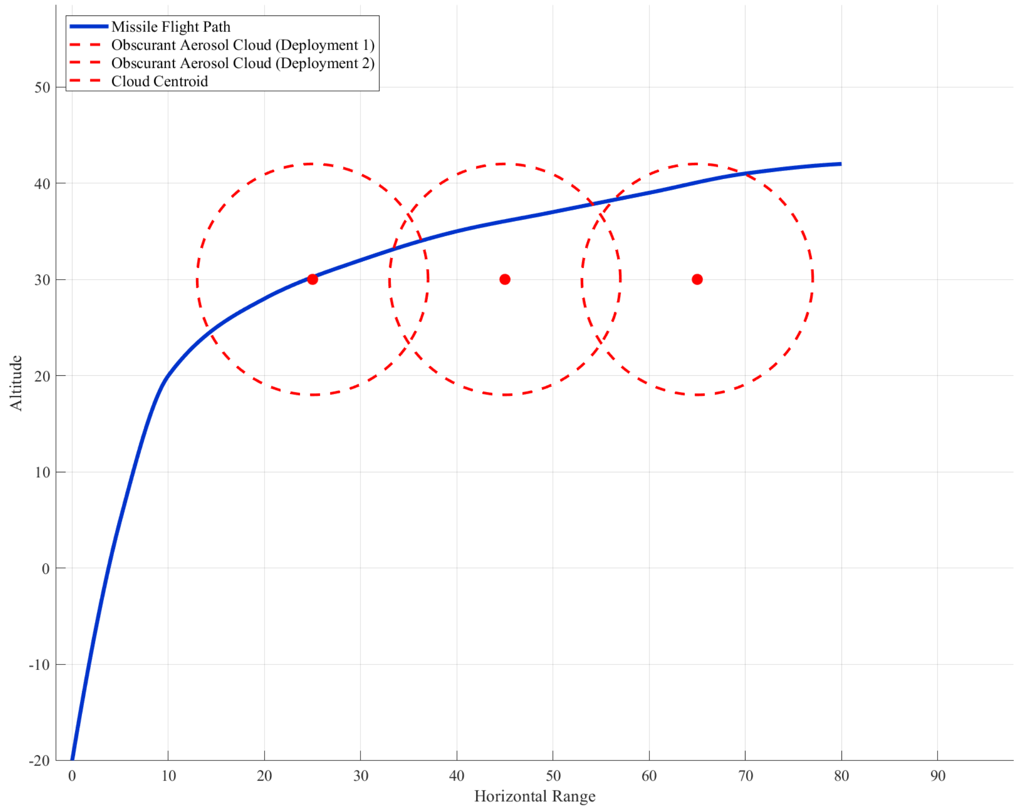

Figure 2 Coordinated Release Effect of Three Smoke Bombs

3.3 Sensitivity Analysis and Discussion

This paper conducts a sensitivity analysis of the results obtained from the genetic algorithm, investigating the effects of flight speed, release delay, and detonation delay on the jamming duration. The experiments show that flight speed has a relatively small impact on jamming duration, while release delay and detonation delay have a significant effect. As the release delay and detonation delay increase, the jamming duration gradually increases (Figure 3). However, the increase in the jamming duration tends to stabilize, highlighting the importance of finding an optimal balance during the optimization process.[5]

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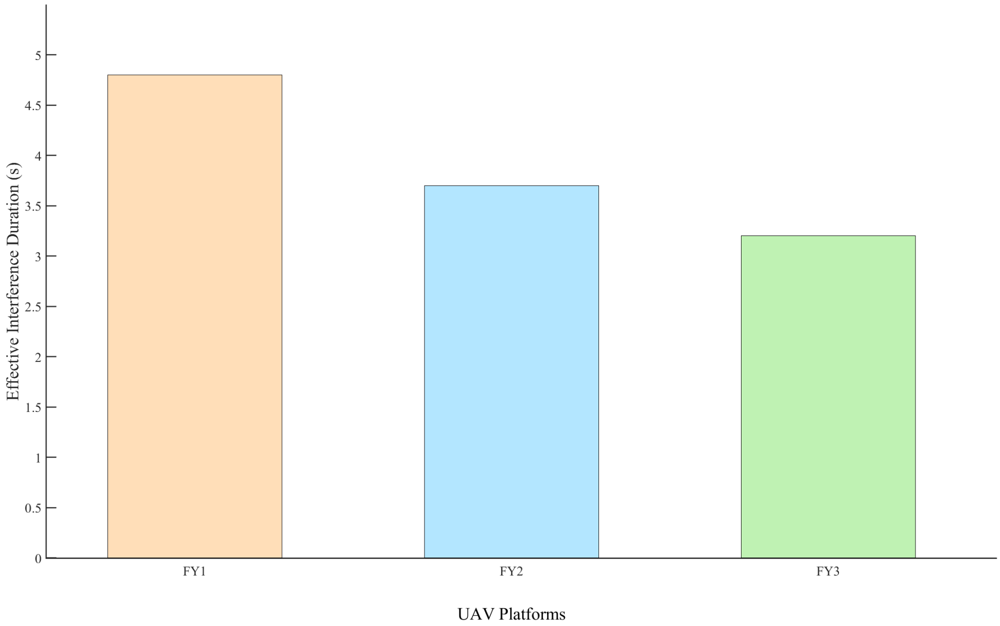

Figure 3 The Relationship between Flight Speed and Jamming Duration

4. Conclusion

This paper presents a UAV smoke screen jamming deployment strategy based on genetic algorithms, optimizing both single bomb and multi-bomb coordination strategies. In the single bomb optimization, by adjusting the flight path and release timing, the jamming duration increased from 1.3872 seconds to 5.24 seconds. In the multi-bomb coordination optimization, by optimizing the release timing and detonation delays of the smoke bombs, the total jamming duration reached 11.22 seconds, approximately 2.9 times longer than the single bomb release. The optimization results show that genetic algorithms can effectively improve the jamming duration of smoke bombs, providing effective technical support for air defense operations.

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