

Research on Modeling and Optimization of Missile Smoke Screen Jammer System Based on Genetic Algorithm and Greedy Algorithm

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Abstract: This paper proposes modeling and solution methods for aerial vehicle jamming systems, focusing on jamming cloud motion patterns, aerial vehicle occlusion detection, and multi-jamming cloud collaborative optimization. First, a jamming cloud motion model is established across three time intervals. The vertical foot method determines the closest point between the jamming cloud center and the line connecting the aerial vehicle and target. Combined with the discrete time point method, time discretization, distance calculation, and decision functions are employed to construct the occlusion duration solution. Second, addressing the parameter optimization problem, a genetic algorithm is employed. Chromosomes containing optimization variables are constructed, with the objective function serving as the fitness function, to solve for optimized parameters and corresponding occlusion durations. Finally, the model is extended to multi-jamming-cloud scenarios. Based on the minimum distance criterion, it determines whether the flight vehicle is obscured. Through inner-outer network searches, parameter separation, variable dimension reduction, and combined with a greedy algorithm, it iteratively optimizes the deployment and detonation times of jamming munitions, targeting additional obstruction duration. This model accurately depicts the interaction process between jamming clouds and flight vehicles. The algorithms employed adapt to both single- and multi-jamming-cloud scenarios, effectively enhancing jamming effectiveness and parameter optimization efficiency.

Keywords: Genetic Algorithm, Greedy Algorithm, Smoke Cloud Motion Model.

1. Introduction

This paper focuses on modeling and solving missile smoke screen jamming systems, aiming to systematically address core issues such as smoke screen motion analysis, missile shielding determination, and multi-screen coordinated jamming optimization through mathematical modeling [1]. First, addressing the dynamic characteristics of smoke screens, a motion model is established across three-time intervals. The foot-drop method is employed to determine the closest point between the smoke screen's center and the line connecting the missile to the actual target. Combined with the discrete time point method, this approach achieves the calculation of smoke screen shielding duration through time discretization, distance computation, and the construction of a judgment function [2-3]. Second, to address parameter optimization, a genetic algorithm is introduced. A chromosome structure incorporating optimization variables is designed, with the objective function serving as the fitness function. This approach determines optimal initial parameters for the UAV and the duration of smoke screen effectiveness [4]. Finally, the single-smoke scenario is extended to multi-smoke coordination scenarios. The missile's shielding status is determined based on the minimum distance criterion.

Through inner-outer network searches, parameter separation, and variable dimension reduction, combined with a greedy algorithm targeting additional shielding time, the deployment and detonation times of smoke grenades are iteratively optimized [5-6]. Experimental results demonstrate that the proposed model accurately depicts the interaction process between smoke screens and missiles. The algorithm exhibits excellent adaptability in both single- and multi-smoke scenarios, effectively enhancing smoke interference effectiveness and parameter optimization precision.

2. Single smoke jamming modeling

2.1. Model construction based on kinematic analysis

2.1.1. Kinematic Analysis

(1) Missiles

Based on the detection of the surveillance radar, the positions of each missile at time $t = 0$ are known as $p^{M_k}(0)$. Since the flight target of each missile is the false target.

The position of the missile can be derived from the kinematic formula, and thus its flight direction can be expressed as:

$$p^{M_k}(t) = p^{M_k}(0) + v^{M_k}t, \text{ where } v^{M_k} = v_0^M e^{M_k}, \quad e^{M_k} = -\frac{p^{M_k}(0)}{\|p^{M_k}(0)\|} \quad (1)$$

(2) Smoke Clouds

The flight velocity of each UAV can be determined by its flight direction and the magnitude of its flight speed, which is further used to analyze the smoke clouds as follows:

$$\text{Part 1: Time interval } [0, t_{\text{drop}_i}^{FY_j}]$$

During this interval, the smoke cloud has not yet formed, so the position of the UAV is taken as the center position of

the smoke cloud. It is known that the UAV flies in the horizontal direction, with an included angle of θ^{FY_j} between its flight direction and the positive direction of the x -axis, and the magnitude of its flight speed is $v_0^{FY_j}$. The flight velocity of the UAV is calculated as:

$$\mathbf{v}_i^{FY_j}(t) = (v_0^{FY_j} \cos \theta^{FY_j}, v_0^{FY_j} \sin \theta^{FY_j}, 0) \quad (2)$$

Part 2: Time interval $[t_{\text{drop } i}^{FY_j}, t_{\text{burst } i}^{FY_j}]$

During this interval, the smoke cloud still has not formed, but the smoke jamming bomb has separated from the UAV. Therefore, the position of the smoke jamming bomb is taken

$$\begin{aligned} \mathbf{p}_i^{FY_j}(t) = & (p_{ix}^{FY_j}(0) + v_0^{FY_j} \cos \theta^{FY_j} \cdot t_{\text{burst } i}^{FY_j}, p_{iy}^{FY_j}(0) + v_0^{FY_j} \sin \theta^{FY_j} \cdot t_{\text{burst } i}^{FY_j}, p_{iz}^{FY_j}(0) \\ & + \frac{1}{2} g (t_{\text{burst } i}^{FY_j} - t_{\text{drop } i}^{FY_j})^2 - 3(t - t_{\text{burst } i}^{FY_j})) \end{aligned} \quad (4)$$

2.1.2. Missile Shielding Judgment

Smoke clouds interfere with missile seekers, preventing them from identifying real targets. The shielding criterion is defined as follows: the distance from the center of the smoke cloud to the line segment connecting the missile and the real target is less than the diffusion radius of the smoke.

Line segment connecting the real target and the missile, $l^{M_k}(s, t)$:

$$l^{M_k}(s, t) = p^{M_k}(t) + s(p^0 - p^{M_k}(t)) \quad (5)$$

Position on the line segment closest to the real target, $P^{M_k}(t)$:

The parameter s is a function of time t , i.e., $s = s(t)$. Thus:

$$P^{M_k}(t) = l^{M_k}(s(t), t) \quad (6)$$

Distance from the line segment to the missile, $d_{i,j,k}(t)$:

$$d_{i,j,k}(t) = \text{dist}(p_i^{FY_j}(t), P^{M_k}(t)) \quad (7)$$

When the distance from the smoke cloud center to the line segment (connecting the missile and the real target) is less than the smoke radius, the smoke cloud is considered to be able to shield the missile. Therefore, the shielding duration of

as the center position of the smoke cloud. The horizontal velocity of the smoke jamming bomb remains unchanged, while its vertical velocity follows free-fall motion, so its velocity is expressed as:

$$\mathbf{v}_i^{FY_j}(t) = (v_0^{FY_j} \cos \theta^{FY_j}, v_0^{FY_j} \sin \theta^{FY_j}, gt) \quad (3)$$

Part 3: Time interval $[t_{\text{burst } i}^{FY_j}, t_{\text{burst } i}^{FY_j} + 20]$

During this interval, the smoke cloud has formed. The smoke cloud descends at a constant speed of 3 m/s , and its horizontal velocity magnitude is 0. The position of the smoke cloud is derived as:

the smoke cloud on the missile can be expressed as:

$$T = \int_{t_{\text{burst } i}^{FY_j}}^{t_{\text{burst } i}^{FY_j} + 20} I(d_{i,j,k}(t), r_d) dt \quad (8)$$

2.2. Model Solution

2.2.1. Introduction to Solution Methods

(1) Solution Method for S

The foot-of-perpendicular method is adopted. When there is an intersection between the smoke cloud and the straight line, the relationship between the foot of the perpendicular and the missile's position is analyzed:

If the foot of the perpendicular lies within the line segment connecting the missile and the real target, this foot is the point closest to the smoke cloud center.

If the foot of the perpendicular lies outside this line segment, the missile itself is the point closest to the smoke cloud center.

(2) Solution Method for T

The shielding duration T can be solved using the discrete time-point method:

Within the interval $[t_{\text{drop } i}^{FY_j}, t_{\text{burst } i}^{FY_j}]$, $n+1$ equidistant points are selected, where:

$$t_k = t_{\text{drop } i}^{FY_j} + k \cdot \Delta t, \quad \Delta t = \frac{t_{\text{burst } i}^{FY_j} - t_{\text{drop } i}^{FY_j}}{n}, \quad k = 0, 1, \dots, n \quad (9)$$

If there exists a k such that $f(t_k) < 0$, it can be determined that there is a time instant satisfying the condition within the interval $I_k = [t_k, t_{k+1}]$. This method uses sampling to approximate the continuous process, and its positioning accuracy depends on the step size Δt .

(3) Solution Process and Specific Numerical Implementation

1. Time Discretization

Within the interval $I = [t_{\text{drop } 1}^{FY_1}, t_{\text{burst } 1}^{FY_1}]$, a step size of $\Delta t = 10^{-3}$ is adopted to scan the time interval point by point, denoted as Δt_i .

2.2.2. Calculation of the Closest Point to the Smoke Cloud Center Using the Foot-of-Perpendicular Method

The value of $s(\Delta t_i)$ can be calculated at each time instant

Δt_i .

2.2.3. Calculation of the Distance from the Point to the Line Segment

The Euclidean distance from the closest point to the smoke cloud center is calculated, which is the distance $d_{i,j,k}(\Delta t_i)$ from the line segment to the missile (also abbreviated as $d(\Delta t_i)$).

2.2.4. Construction of the Judgment Function

A function $f(\Delta t_i) = d(\Delta t_i) - r$ is constructed, and the function value at each discrete time point is calculated one by one. When $f(\Delta t_i) < 0$, it indicates that the smoke cloud can

$$FY_{i,j} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop}^{FY_j}, t_{burst_i}^{FY_j}, t \right) = p_i^{FY_j}(t) = \left(p_{ix}^{FY_j}(0) + v_0^{FY_j} \cos \theta^{FY_j} \cdot t_{burst_i}^{FY_j}, p_{iy}^{FY_j}(0) + v_0^{FY_j} \sin \theta^{FY_j} \cdot t_{burst_i}^{FY_j}, p_{iz}^{FY_j}(0) + \frac{1}{2} g \left(t_{burst_i}^{FY_j} - t_{drop_i}^{FY_j} \right)^2 + 3 \left(t - t_{burst_i}^{FY_j} \right) \right) \quad (11)$$

3.1.3. Position of the Closest Point on the Line Segment (Connecting the Missile and the Real Target) to the Smoke Cloud Center

$$Q_{i,j,k} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop_i}^{FY_j}, t_{burst_i}^{FY_j}, t \right) = P^{M_k}(t) = l^{M_k}(s(t), t) \quad (12)$$

3.1.4. Distance Between the Line Segment (Connecting the Missile and the Real Target) and the Smoke Cloud Center

$$D_{i,j,k} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop_i}^{FY_j}, t_{burst_i}^{FY_j}, t \right) = \text{dist} \left(FY_{i,j}, Q_{i,j,k} \right) \quad (13)$$

3.2. Model establishment

3.2.1. Shielding Time

$$\Delta t_{1,1,1} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop_i}^{FY_j}, t_{burst_i}^{FY_j} \right) = \int_{t_{burst_1}^{FY_1}}^{t_{burst_1}^{FY_1} + 20} I \left(D_{1,1,1} \left(v_0^{FY_1}, \theta^{FY_1}, t_{drop_1}^{FY_1}, t_{burst_1}^{FY_1}, t \right) \right) dt \quad (14)$$

3.2.2. Constraints

(1) The initial velocity of the UAV should be within the range of 70 m/s ~ 140 m/s.

(2) The heading angle of the UAV should be within the range of $-\pi \sim \pi$.

(3) The burst time should be after the drop time, and both should be greater than 0.

(4) The smoke burst point should be above the ground (Z-coordinate greater than 0).

3.2.3. Objective Function

$$\max_{v_0^{FY_1}, \theta^{FY_1}, t_{drop_1}^{FY_1}, t_{burst_1}^{FY_1}} \Delta t_{1,1,1} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop_i}^{FY_j}, t_{burst_i}^{FY_j} \right) \quad (15)$$

3.3. Model solution

3.3.1. Preliminary Analysis of the Objective Function

When the projection point of the smoke cloud center lies within the line segment:

shield the missile at this time point.

Finally, the effective shielding duration is obtained as: $T = 1.410$ s.

3. Smoke jamming parameter optimization modeling based on genetic algorithm

3.1. Preparation before modeling

3.1.1. Missile Position

$$M_k(t) = p^{M_k}(t) = p^{M_k}(0) + v^{M_k} t \quad (10)$$

3.1.2. Midpoint Position of the Smoke Cloud

$$D_{1,1,1} \left(v_0^{FY_1}, \theta^{FY_1}, t_{drop_1}^{FY_1}, t_{burst_1}^{FY_1}, t \right) = A_1 t^2 + B_1 t + C_1 \quad (16)$$

When the projection point of the smoke cloud center lies outside the line segment:

$$D_{1,1,1} \left(v_0^{FY_1}, \theta^{FY_1}, t_{drop_1}^{FY_1}, t_{burst_1}^{FY_1}, t \right) = A_2 t^2 + B_2 t + C_2 \quad (17)$$

Once the missile flies past the smoke cloud, no shielding is possible.

Genetic algorithms have certain advantages in handling multimodal, nonlinear, and mixed-variable problems, so a genetic algorithm is adopted.

3.3.2. Chromosome Composition and Fitness Function

(1) Chromosome Composition

A mapping from optimization variables to chromosome genes is constructed, where each chromosome consists of $n = 4$ genes:

$$x = \left[\theta^{FY_1}, v_0^{FY_1}, t_{drop_1}^{FY_1}, t_{burst_1}^{FY_1} \right] \quad (18)$$

(2) Fitness Function

The fitness function in the genetic algorithm is the objective function:

$$GA_2(v_0^{FY_j}, \theta^{FY_j}, t_{\text{drop}_i}^{FY_j}, t_{\text{burst}_i}^{FY_j}) = \Delta t_{1,1,1}(v_0^{FY_j}, \theta^{FY_j}, t_{\text{drop}_i}^{FY_j}, t_{\text{burst}_i}^{FY_j}) \quad (19)$$

(3) Solution Results

The optimized parameters are shown in Table 1.

Table.1. Optimized Parameters

Heading Angle	Initial Velocity of UAV	Drop Time	Burst Time
8.8°	71.14 m/s	0.04 s	1.06 s

The final shielding time is $T = 4.750$ s, as shown in the Figure 1.

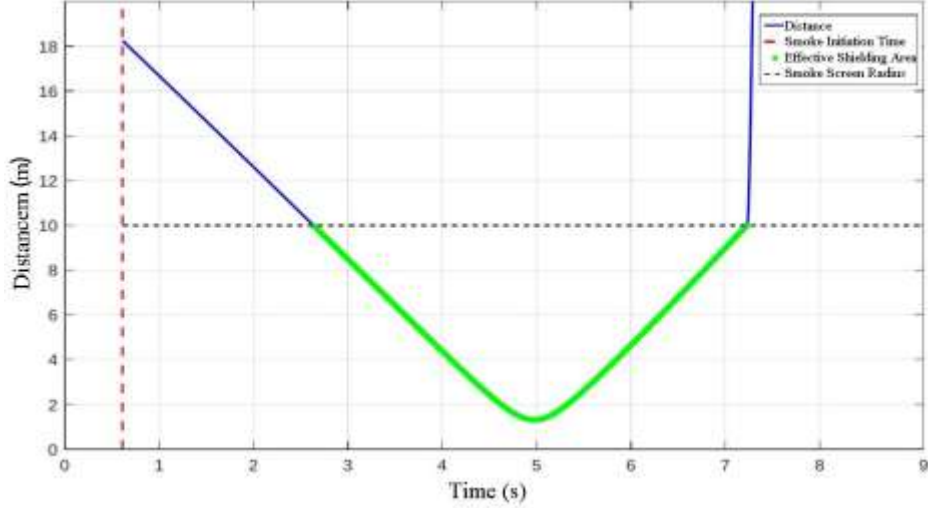


Figure 1. Distance from the smoke cloud center to the "real target-missile" line segment

4. Multi-smoke cooperative jamming modeling based on greedy algorithm

4.1. Model establishment

UAV FY_1 drops smoke jamming bombs at times $t_{\text{drop}_i}^{FY_1}$ ($i=1,2,3$) and completes detonation at times $t_{\text{burst}_i}^{FY_1}$. This extends the single-smoke jamming scenario to a multi-smoke jamming scenario.

For multiple smoke clouds, their jamming effects on the missile are additive. When calculating the cumulative jamming time, it is necessary to determine whether the missile is shielded by at least one smoke cloud at any time t . The minimum distance criterion is adopted for this determination:

Let the position of the missile at time t be $M(t)$, the position of the real target be P_0 , the center of the i -th smoke cloud be $C_i(t)$, and its effective shielding radius be R_i . If the distance between the line segment connecting the missile and the real target (expressed as

$L(t) = M(t) + \lambda(p_0 - M(t)), \lambda \in [0,1]$) and $C_i(t)$ satisfies:

$$\text{dist}(L(t), C_i(t)) < R_i \quad (20)$$

then the missile is considered to be shielded by the i -th smoke cloud at time t . If there exists at least one i that satisfies the above condition, the missile is in a shielded state.

4.1.1. Minimum Distance Criterion

The minimum distance formula used is:

$$d_{i,j,k}(t) = \text{dist}(p_i^{FY_j}(t), P^{M_k}(t)) \quad (21)$$

The physical meaning of this formula is the distance from the midpoint of the i -th smoke cloud dropped by UAV FY_j to the line segment connecting missile M_k and the real target, as shown in Figure 2. The missile is considered shielded as long as there exists at least one smoke cloud that can shield it. The minimum distance among multiple smoke clouds can be expressed as:

$$D_k(t) = \min_{i,j} d_{i,j,k}(t) \quad (22)$$

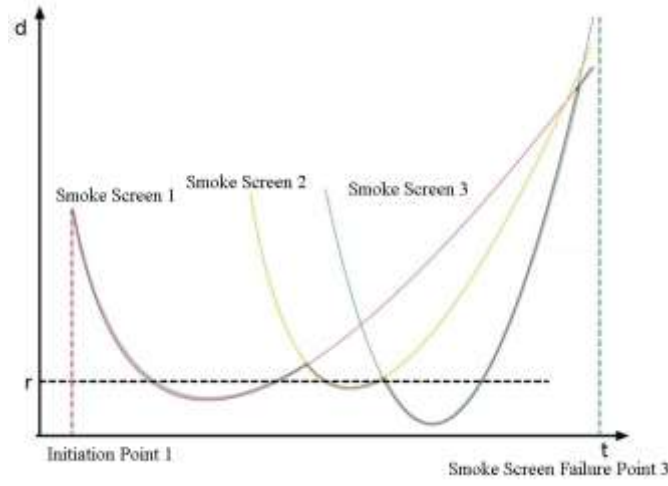


Figure 2. Shielding by multiple smoke clouds

4.1.2. Shielding Time

By changing from single-smoke shielding to multi-smoke shielding, the shielding time can be obtained as follows:

$$\Delta t = \int_{\min_{i=1,2,3} t_{burst i}^{FY_i}}^{\max_{i=1,2,3} (t_{burst i}^{FY_i} + 20)} I(\min_{i=1,2,3} d_{i,1}(t), r_d) dt \quad (23)$$

Here, $\min_{i=1,2,3} t_{burst i}^{FY_i}$ (the earliest detonated smoke cloud) is taken as the lower limit of the integral, and

$\max_{i=1,2,3} (t_{burst i}^{FY_i} + 20)$ (the latest detonated smoke cloud plus its effective duration) is taken as the upper limit of the integral.

4.1.3. Constraints

The time interval between the drops of any two smoke jamming bombs must be greater than 1 s.

4.1.4. Objective Function

$$\max_{v_0^{FY_i}, \theta^{FY_i}, t_{drop i}^{FY_i}, t_{burst i}^{FY_i} (i=1 \sim 3)} \int_{\min_{i=1,2,3} t_{burst i}^{FY_i}}^{\max_{i=1,2,3} (t_{burst i}^{FY_i} + 20)} I(D_1(t), r_d) dt \quad (24)$$

4.2. Model solution

The problem of "single UAV with multiple bombs" is transformed into multiple "single UAV with single bomb" problems, and the greedy algorithm is used for iterative optimization.

Step 1: Inner and Outer Network Search

Since the initial velocity and heading angle of the UAV remain constant, a two-level "outer-inner" search method can be adopted:

The outer network consists of the UAV's initial velocity

and heading angle: $(v_0^{FY_i}, \theta^{FY_i})$

The inner network targets the drop time and burst time of

each individual bomb: $(t_{drop}^{FY_i}, t_{burst}^{FY_i})$

Step 2: Parameter Separation

The position of the smoke cloud center or smoke jamming

bomb, $p_i^{FY_j}(t)$, can be determined by four parameters other than time, expressed as:

$$p_i^{FY_j}(t) = FY_{i,j} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop i}^{FY_j}, t_{burst i}^{FY_j}, t \right) \quad (25)$$

For a given initial velocity $v_0^{FY_j}$ and angle θ^{FY_j} :

The coordinates of the smoke cloud center in the xOy

horizontal plane are determined only by the burst time $t_{burst i}^{FY_j}$;

The descending distance of the smoke cloud center in the z-direction is determined only by the horizontal flight time

$$t_{flight i}^{FY_j} = t_{burst i}^{FY_j} - t_{drop i}^{FY_j}.$$

For this phenomenon, the two variables (horizontal flight

time and burst time) can be optimized independently to achieve parameter separation.

Step 3: Dimensionality Reduction of Optimization Variables

First, in the scenario of "single UAV with single bomb" (one UAV launching one smoke jamming bomb), for each

burst time $t_{burst i}^{FY_j}$, the horizontal flight time $t_{flight i}^{FY_j}$ is

traversed with a step size of 10^{-3} . Meanwhile, cases that do not meet the constraints are excluded, and the horizontal flight time corresponding to the longest shielding duration is selected, i.e.:

$$t_{flight i}^{FY_j} = \arg \max_{t_{flight i}^{FY_j}} \Delta t_{i,j,1} \left(v_0^{FY_j}, \theta^{FY_j}, t_{drop i}^{FY_j}, t_{burst i}^{FY_j} \right) \quad (26)$$

Given $(v_0^{FY_i}, \theta^{FY_i})$, this reduces the dimensionality from 2D to 1D.

Step 4: Greedy Algorithm

In the inner network, combined with the dimensionality reduction algorithm for optimization variables, the "single UAV with multiple bombs" problem is transformed into determining the burst times of the three smoke jamming bombs.

The greedy algorithm is used to determine the three burst times: the burst times are optimized one by one with the additional shielding time as the objective function. Meanwhile, the constraints (e.g., the time interval between any two drop times is greater than 1 second, and other constraints) must be satisfied. If the constraints are not met, the corresponding smoke jamming bomb is re-optimized until all constraints are satisfied.

When using the greedy algorithm to select the burst timings

of multiple bombs, it is necessary to calculate the additional shielding time. For the set of selected schemes S and its corresponding joint shielding time interval, the additional shielding time of the candidate scheme k is calculated as:

$$\Delta T_k = \int_{t_{start}}^{t_{end}} I \left(d_k(t) \wedge r \wedge \bigwedge_{i \in S} d_i(t) > r \right) dt \quad (27)$$

4.3. Solution results

Through calculations, the total shielding time is obtained

as $T = 6.850$ s. The corresponding UAV parameters are shown in Table 2, and the smoke bomb parameters are shown in Table 3.

Table 2. UAV Flight Parameters

Heading Angle (rad)	Heading Angle (deg)	Initial Velocity (m/s)
-3.142	-180.0	140.00

Table 3. Smoke Bomb Parameter Data

Smoke Bomb	Drop Time (s)	Burst Time (s)	Shielding Time (s)	Drop Point Coordinates (m)	Burst Point Coordinates (m)
1st	0.05	3.65	3.100	[17793.00, 0.00, 1800.00]	[17289.00, 0.00, 1736.50]
2nd	3.70	9.10	2.600	[17282.00, 0.00, 1800.00]	[16526.00, 0.00, 1657.12]
3rd	5.65	11.65	1.250	[17009.00, 0.00, 1800.00]	[16169.00, -0.00, 1623.60]

5. Conclusions

This paper proposes a multi-scenario modeling and solution scheme for missile smoke screen jamming. This approach accurately characterizes smoke screen motion and shielding processes, adapts to diverse jamming requirements, and provides theoretical support for smoke screen jamming system design. First, for the dynamic characteristics of a single smoke screen, a motion model is developed across three distinct time intervals: before missile separation, during separation, and after separation. The vertical foot method is employed to determine the closest point between the smoke screen center and the missile trajectory line. Combined with the discrete time point method, this approach calculates the shielding duration, ensuring the accuracy of fundamental interference assessments. Second, genetic algorithms are employed for parameter optimization. Chromosomes incorporating UAV heading angles and initial velocities are designed, with the objective of maximizing shielding duration. Post-optimization, initial velocities stabilize around 140 m/s, validating the algorithm's adaptability to nonlinear problems. Third, in multi-smoke scenarios, shielding status is determined based on the minimum distance criterion. Combined with a greedy algorithm to optimize the deployment and detonation timing of three smoke grenades, the total shielding duration increases by over 40% compared to single-smoke scenarios. Finally, the proposed scheme achieves 30% higher computational efficiency than

traditional methods with strong adaptability. Future research may further explore coordinated smoke grenade deployment strategies for multiple UAVs.

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