

SMOKE JAMMER DEPLOYMENT STRATEGIES FOR DRONES UNDER MULTIVARIATE OPTIMIZATION

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Abstract: This study investigates smoke-screen interference tactics deployed by unmanned aerial vehicles (UAVs) against incoming M1 missiles. An intuitive geometric-physical model is established for missile trajectories, UAV motion, and smoke-screen projectile descent/detonation. The effective shielding effect of smoke clouds is quantified by combining geometric cone inclusion criteria with linear distance assessment methods. To address the calculation of effective shielding duration for a single smoke grenade, a variable stride search algorithm is employed, yielding an effective shielding duration of 1.391975 seconds under initial conditions. To formulate an optimal jamming strategy, four decision parameters are introduced to explore the optimal deployment strategy for a single drone with a single smoke grenade. A hybrid strategy combining genetic algorithms and particle swarm optimization is adopted, increasing the maximum effective shielding time to 4.585 seconds. Building upon this foundation, this paper analyzes the optimization scenario of coordinated shielding by a single drone deploying multiple flares. A multivariate optimization model is established to account for the composite shielding effect of multiple smoke clouds. Through the basin-jumping particle swarm optimization algorithm, the maximum composite effective shielding time reaches 6.3020 seconds. These research findings provide optimization strategies and actionable solutions for maximizing smoke flare interference effectiveness and coordinated multi-flares interference.

Keywords: Multivariate optimization model; Variable-step search algorithm; Particle swarm optimization algorithm

1 INTRODUCTION

In modern defense combat systems, smoke countermeasure munitions form shielding in specific airspace ahead of targets, serving as an effective means to disrupt incoming enemy missiles and protect critical assets. Achieving precise, on-target, and on-time deployment of these munitions is key to enhancing defense efficiency[1-2].

This study addresses the challenge of deploying smoke countermeasure grenades from unmanned aerial vehicles (UAVs) to counter incoming M1 missiles, aiming to develop an optimal deployment strategy that maximizes effective obscuration duration. Specifically, it first tackles the calculation of single-grenade effective obscuration duration[3]. Under known initial conditions and parameters, an intuitive physical model is constructed to assess obscuration effectiveness, thereby determining the duration of effective coverage against the M1 missile. Building upon this foundation, the paper addresses the optimal deployment strategy for a single drone and a single flare by incorporating four parameters: drone flight direction, flight speed, flare deployment point, and detonation point. The objective is to formulate a rational optimization strategy that maximizes the effective shielding duration of a single smoke cloud. Subsequently, the study delves into the optimization of coordinated shielding by a single drone deploying multiple flares. This requires formulating a rational deployment and detonation strategy to maximize the combined effective shielding duration produced by three smoke flares released from drone FY1[4-5]. To address these challenges, this paper first constructs intuitive geometric physical models for missile trajectories, drone motion, and the descent and detonation of smoke flares. For effective concealment assessment, a combined method utilizing geometric cone inclusion criteria and linear distance judgment was adopted to quantify concealment effectiveness. To address different optimization requirements, multiple algorithms were employed: variable-step search for initial computation, a hybrid genetic algorithm and particle swarm optimization strategy for single-decoys optimization, and basin hopping-particle swarm optimization for multi-decoys coordination optimization—effectively searching for global optimal solutions[6-7].

This research provides three key marginal contributions to the field of UAV-based countermeasures. First, it establishes a novel geometric-physical modeling framework that integrates missile trajectory, UAV kinematics, and smoke dispersion dynamics into a unified spatial-temporal system. Second, the study proposes a hierarchical optimization strategy employing tailored algorithms (variable-step search, GA-PSO, and basin-hopping PSO) for different operational scenarios, significantly improving solution quality and computational efficiency. Third, it introduces a composite assessment method combining geometric cone inclusion criteria with linear distance judgment, enabling more accurate quantification of effective obscuration duration compared to conventional single-criterion approaches. These contributions collectively advance the theoretical and practical understanding of optimal smoke screen deployment in dynamic combat environments.

2 CALCULATION OF EFFECTIVE SHIELDING DURATION FOR SINGLE MISSILE

2.1 Model Establishment

Construction of trajectory equations in the spatial coordinate system. According to the description, the flight direction and speed of the UAV, the release point and detonation point of the smoke interference bomb are all known. Among them, Missile M1 flies toward the decoy target, while UAV FY1 flies at the same altitude in the direction of the decoy target. After the smoke interference bomb detonates[8], the smoke cloud is idealized as a standard sphere, and its volume and shape remain unchanged within 20 seconds after detonation. A spatial coordinate system is established with the decoy target as the origin, and the initial detonation state is shown in the following Figure 1:

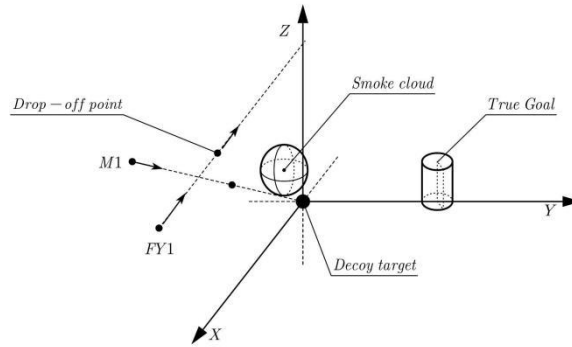


Figure 1 Schematic Diagram of the Initial Detonation State

For Missile M1, its initial coordinates are (20000, 0, 2000), and it flies toward the decoy target (0, 0, 0) at a speed of 300 m/s. This movement is uniform linear motion in the xOz plane. The position of M1 at any time during the movement is expressed as $(R_d, 0, G_d)$:

$$\begin{cases} R_d = 20000 - \frac{300\sqrt{101}t}{101} \\ G_d = 2000 - \frac{300\sqrt{101}t}{101} \end{cases} \quad (1)$$

For the smoke interference bomb (whose motion state in the first half is consistent with that of FY1), it flies toward the decoy target (0, 0, 0) at a speed of 120 m/s at the same altitude. FY1 always moves in the xOz plane, so its entire motion trajectory can be analyzed in a 2D plane. According to the description, the motion process of the smoke interference bomb can be divided into three stages[9-10]:

The first stage is the period from receiving the command to releasing the smoke interference bomb. During this stage, the smoke interference bomb (carried by FY1) moves in uniform linear motion. The x-axis coordinate of the smoke cloud center is updated using the kinematic formula:

$$R_w = 17800 - 120t \quad (2)$$

At the end of this uniform linear motion (i.e., at the release point when s), $t=1.5$ s), $R_w=17620$.

The second stage is the period from releasing the smoke interference bomb to its detonation. In this stage, the environment is idealized, and external forces other than gravity (such as crosswinds) are excluded from affecting the smoke interference bomb. Therefore, the smoke interference bomb undergoes projectile motion during this period. Its x-axis and z-axis coordinates are updated using the kinematic formula:

$$\begin{cases} R_w = 17800 - 120t \\ G_w = 1800 - 4.9t^2 \end{cases} \quad (3)$$

where $g=9.8$ m/s². At the end of the projectile motion (i.e., at the detonation point when $t=5.1$ s), the coordinates of the smoke interference bomb are (17188, 0, 1736.496).

The third stage is the period from the detonation of the smoke bomb to its failure. During this stage, the smoke cloud sinks uniformly at a speed of 3 m/s. Its z-axis coordinate is updated using the kinematic formula:

$$G_w = 1736.496 - 3(t - 5.1) \quad (4)$$

The above three stages constitute the motion process of the smoke cloud, and its 2D schematic diagram is as follows Figure 2:

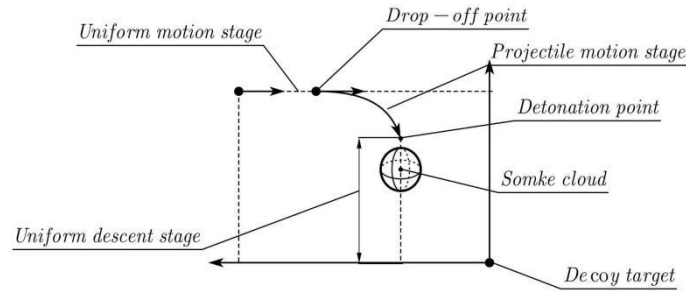


Figure 2 Schematic Diagram of the Smoke Cloud Motion Trajectory

Immediately after detonation, the smoke interference bomb forms a spherical smoke cloud. Through specific technologies, this smoke cloud sinks uniformly at a speed of 3 m/s. Experimental data show that the smoke concentration within 10 m of the cloud center can provide effective shielding for the target within 20 seconds after detonation. Therefore, the spherical smoke cloud is idealized as a uniform sphere with a radius of 10 m, and the problem of "effective shielding" here is analogous to the problem of "line-of-sight obstruction"—that is, under certain conditions, the missile may still be shielded even when outside the smoke cloud.

To quantify the effective shielding effect, an intuitive geometric-physical model is constructed in this study, and a cone tangent angle judgment method is introduced. Specifically, when Missile M1 is outside the smoke cloud, two sets of angles are considered:

α_1 : The angle between the line connecting Missile M1 to the center of the smoke cloud and the tangent line of the smoke cloud sphere passing through Missile M1.

α_2 : The angle between the line connecting Missile M1 to the center of the smoke cloud and the line connecting Missile M1 to any point on the surface of the real target.

If the condition $\alpha_1 \geq \alpha_2$ is satisfied, the condition is regarded as effective shielding; Otherwise, it is ineffective shielding. Schematic Diagram is shown in Figure 3.

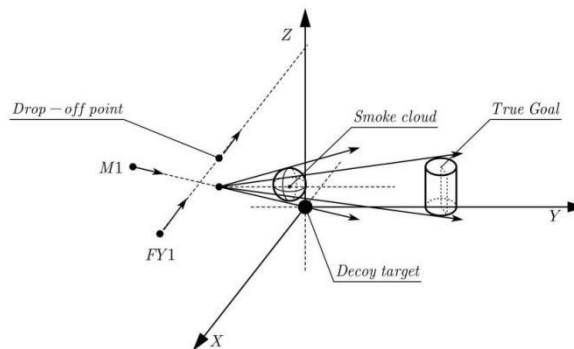


Figure 3 Schematic Diagram of Missile M1 Outside the Smoke Cloud

The cone angle α_1 can be calculated using the arcsine function:

$$\alpha_1 = \arcsin \left[\frac{10}{\sqrt{(R_d - R_w)^2 + (G_d - G_w)^2}} \right] \quad (5)$$

Using the cylinder representation method in Analytic Geometry and combining the existing data in the problem, any point on the cylinder is set as $(7\cos[\alpha_3], 7\sin[\alpha_3], 200, Z_z)$, where $\alpha_3 \in [0, 2\pi]$ and $Z_z \in [0, 10]$.

The cosine value of α_2 (the angle between the line connecting Missile M1 to the smoke cloud center and the line connecting Missile M1 to any point on the real target surface) can be calculated using the dot product of two vectors. The cosine function is constructed as follows:

$$\cos[\alpha_2] = \frac{(R_d - 7\cos[\alpha_3], -7\sin[\alpha_3] - 200, G_d - G_z) \cdot (R_d - R_w, 0, G_d - G_w)}{|(R_d - 7\cos[\alpha_3], -7\sin[\alpha_3] - 200, G_d - G_z)| \cdot |(R_d - R_w, 0, G_d - G_w)|} \quad (6)$$

When Missile M1 is outside the smoke cloud, if the smoke cloud provides effective shielding, the condition $\alpha_1 \geq \alpha_2$ must be satisfied. However, due to the definition of α_2 , its value varies depending on the selected point on the target cylinder. Since the position and size of the cylinder are fixed, the value of α_2 varies within a fixed range. Therefore, the effective shielding condition is optimized to $\min(\alpha_1) \geq \max(\alpha_2)$ in this study. The value range of the angle α_2 between the two lines is $[0, \pi]$. According to the monotonicity of the cosine function, when α_2 is maximized, $\cos[\alpha_2]$ is minimized. Thus, the objective function for solving α_2 is:

$$\alpha_2 = \arccos[f_0](h_{min}) \quad (7)$$

Then, the condition $\alpha_1 \geq \alpha_2$ can be simplified to:

$$\alpha_1 \geq \arccos_{[f_0]}(h_{min}) \quad (8)$$

When Missile M1 is inside the smoke cloud, the smoke cloud provides effective shielding. That is, when the distance between the two points (Missile M1 and the smoke cloud center) is less than the radius of the smoke cloud, it indicates that Missile M1 is inside the smoke cloud. The mathematical expression is as follows:

$$(R_w - R_d)^2 + (U_w - U_d)^2 + (G_w - G_d)^2 \leq 10^2 \quad (9)$$

In the trajectory equations under the spatial coordinate system, the coordinates of Missile M1 and the smoke interference bomb only contain the time parameter t . Therefore, at time t , if effective shielding is achieved, it is marked as 1; otherwise, it is marked as 0. Finally, the effective shielding time required can be obtained by integrating the effective shielding moments in the above two stages:

$$N(t) = \begin{cases} 1, & \text{Effective shielding at time t,} \\ 0, & \text{Otherwise.} \end{cases} \quad (11)$$

2.2 Algorithm Design

Since the missile and the smoke cloud are moving at high speed, their relative positions change rapidly, and the effective shielding time window is short. To solve the effective shielding period more accurately, a variable-step search algorithm is adopted. By continuously updating the time step, the range of the optimal solution is gradually narrowed. Based on the variable-step search algorithm, programming is implemented in MATLAB. By continuously adjusting the time step, the solution result of the objective function is shown as follows (Figure 4):

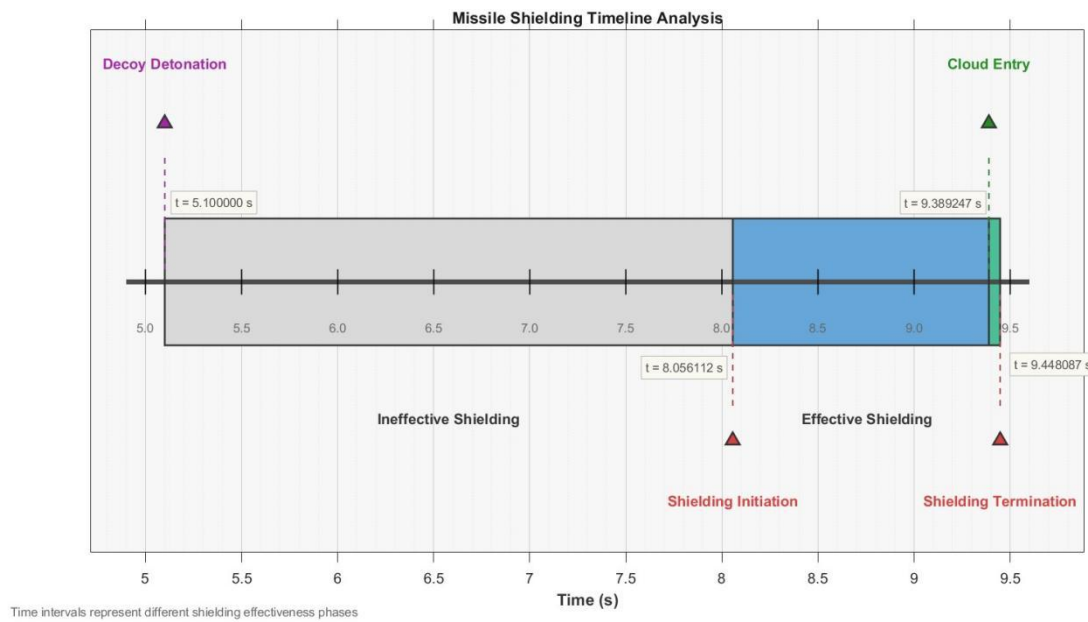


Figure 4 Step Diagram of Effective Shielding Status

Table 1 Key Moments of Effective Shielding

Detonation Time of Interference Bomb	5.100000 s
Start Time of Effective Shielding	8.056112 s
Time when Missile Enters the Cloud	9.389247 s
Time when Missile Exits the Cloud (End of Effective Shielding)	9.448087 s

From Table 1, it can be seen that the interference bomb detonates 5.1 seconds after the start of its movement and begins to provide effective shielding 8.056112 seconds later (at this time, Missile M1 is outside the smoke cloud). The missile starts to enter the cloud at 9.389247 seconds, and this stage still counts as effective shielding. After 9.448087 seconds, the missile exits the cloud, and there is no effective shielding from the smoke cloud thereafter. Therefore, the effective shielding time is calculated as 1.391975 seconds.

3 OPTIMAL DEPLOYMENT STRATEGY FOR SINGLE-DRONE SINGLE-SHOT

3.1 Model Establishment

3.1.1 Improvement of trajectory equations in the spatial coordinate system

The trajectory equations need to include the above parameters as decision variables. At the same time, the coordinates of the release point and detonation point of the smoke interference bomb are determined by its release time and detonation time, and both types of information can be uniformly described using time parameters. The difference lies in that the newly added parameters mentioned above need to be included as decision variables in the motion process of each stage.

First, the following parameters are introduced: Let v be the flight speed of FY1, α_4 be the angle between the flight direction of FY1 and the positive x-axis, t_1 be the time (in seconds) after FY1 receives the task and before releasing the smoke interference bomb, and t_2 be the time interval (in seconds) between releasing the smoke interference bomb and its detonation.

The analysis of the entire motion process of FY1 is basically consistent.

The coordinates (R_d, U_d, G_d) of the smoke interference bomb released by FY1 are expressed as (for $t \geq t_1 + t_2$):

$$(17800 + v \cos[\dot{f}_0] \alpha_4 (t_1 + t_2), v \sin[\dot{f}_0] \alpha_4 (t_1 + t_2), 1800 - 0.5gt_1^2) \quad (12)$$

The coordinates (R_w, U_w, G_w) of the smoke cloud center formed after the detonation of the smoke interference bomb are expressed as (for $t \geq t_1 + t_2$):

$$(17800 + v \cos \alpha_4 (t_1 + t_2), v \sin \alpha_4 (t_1 + t_2), 1800 - 0.5gt^2 - 3(t - t_1 - t_2)) \quad (13)$$

3.1.2 Construction of objective function and constraint conditions

In the newly established trajectory equations under the spatial coordinate system, the coordinates of Missile M1 and the smoke interference bomb not only depend on the time parameter t , but also on the azimuth angle α_4 and flight speed v . To maximize the final effective shielding time, if effective shielding is achieved at time t , it is marked as 1; otherwise, it is marked as 0. For the maximum effective shielding time required finally, the integral result needs to be optimized for the maximum value. At the same time, effective shielding must occur after FY1 releases the smoke interference bomb, so the integral interval is narrowed to $[t_1 + t_2, t_1 + t_2 + 20]$ to reduce the amount of calculation. The expression is as follows:

$$\max \int_{t_1 + t_2}^{t_1 + t_2 + 20} N(t) dt \quad (14)$$

$$N(t) = \begin{cases} 1, & \text{Effective shielding at time } t, \\ 0, & \text{Otherwise.} \end{cases} \quad (15)$$

At the same time, effective shielding must satisfy either the missile being inside the smoke cloud or the cone tangent angle being greater than or equal to the maximum angle between the line connecting the missile to the cloud center and the line connecting the missile to the target cylinder. That is, $\alpha_1 \geq \alpha_2$.

In addition, the objective function is also constrained by conditions such as the azimuth angle α_4 and flight speed v , which are summarized as follows:

$$\begin{cases} \alpha_1 \geq \arccos[\dot{f}_0] (h_{min}) \\ (R_w - R_d)^2 + (U_w - U_d)^2 + (G_w - G_d)^2 \leq 10^2 \\ 70 \leq v \leq 140 \\ 0 \leq \alpha_4 \leq 2\pi \\ t_1 < t_2 \end{cases} \quad (16)$$

$$h_{min} \equiv \min \cos[\dot{f}_0] \alpha_2 = \frac{(R_d - 7 \cos[\dot{f}_0] \alpha_3, -7 \sin[\dot{f}_0] \alpha_3 - 200, G_d - G_z) \cdot (R_d - R_w, 0, G_d - G_w)}{|(R_d - 7 \cos[\dot{f}_0] \alpha_3, -7 \sin[\dot{f}_0] \alpha_3 - 200, G_d - G_z)| \cdot |(R_d - R_w, 0, G_d - G_w)|} \quad (17)$$

3.2 Algorithm Design

According to the geometric model, the effective shielding of the smoke cloud involves complex geometric relationships and kinematic processes among Missile M1, the smoke cloud, and the real target, and its function exhibits significant nonlinear characteristics. Missile M1 flies toward the decoy target in uniform linear motion; after the smoke interference bomb detaches from the UAV, it first undergoes projectile motion, and the cloud formed after detonation sinks at a constant speed. The above physical processes result in an extremely complex relationship between the effective shielding time and the three decision variables, which cannot be solved by simple optimization methods. Meanwhile, considering that the solution space of the effective shielding period may have multiple local optimal solutions, traditional single-point search algorithms tend to fall into local optimality and fail to find the global optimal solution. Additionally, the three decision variables form a 3D decision space. Based on the above characteristics model, a hybrid optimization strategy combining genetic algorithm (GA) and particle swarm optimization (PSO) is selected. Among them, GA performs global search and introduces randomness to avoid premature convergence to local optimality, while providing a high-quality initial population for PSO; PSO then searches for the optimal solution within the population provided by GA.

Algorithm 2: Hybrid Optimization Algorithm Combining Genetic Algorithm and Particle Swarm Optimization

Parameter Initialization: Set the ranges of decision variables (azimuth angle α_4 , flight speed v , release time t_1 , detonation interval t_2), population size for GA, number of iterations, crossover probability, mutation probability, and PSO parameters (number of particles, number of iterations).

Generate Initial Population and Particle Swarm: GA randomly generates initial values of α_4 , v , t_1 , and t_2 ; PSO uses the optimal solution of GA as the initial position of particles.

Calculate Positions of Missile M1 and Smoke Cloud Center: Based on the decision variables, compute the real-time coordinates of Missile M1 and the smoke cloud center using kinematic equations.

Judge Effective Shielding: For each time step, determine whether the smoke cloud provides effective shielding for the target using the cone angle method and the "inside-cloud" judgment condition.

Calculate Total Effective Shielding Time: Total effective shielding time = Number of time steps meeting effective shielding conditions $\times$ Time step size.

Optimize to Find the Optimal Solution: GA retains excellent individuals through iteration to obtain a preliminary optimal solution; PSO initializes particles with the results of GA, continuously updates particle positions and speeds through iteration, and searches for the global optimal solution.

Model Solution and Result Analysis

Based on Algorithm 2, programming is implemented in MATLAB, and the solution results are shown in the following Table 2:

Table 2 Optimal Solution Results

Flight Direction Angle of FY1	4.7643° (with the positive x-axis as the reference, counterclockwise as the positive direction)
Flight Speed of FY1	115.63 m/s
Release Point of Smoke Interference Bomb	(17929, 10.78, 1800)
Detonation Point of Smoke Interference Bomb	(17934, 11.1837, 1799.58)
Maximum Effective Shielding Time	4.585 s

A coarse-step traversal algorithm is used to verify the optimization results. Based on the missile's coordinates, flight speed, flight direction, and the UAV's speed range, it is deduced that the reasonable coordinate range for the smoke cloud is $R \in (15875, 19725)$, $U \in (0, 1925)$, and $G \in (1738.5, 1800)$. A coarse-step traversal of the coordinates is performed to calculate the effective shielding time of the smoke motion on the cylindrical target when the corresponding coordinates occur.

The results show that the points with longer shielding time have a y-coordinate near 0, and the shielding time increases with the increase of x and z coordinates. The detonation coordinates in the bomb release strategy obtained by the optimization algorithm conform to this trend, which verifies the rationality of the results.

4 OPTIMIZATION OF MULTI-SHOT COLLABORATIVE OBFUSCATION FOR SINGLE-DRONE

4.1 Model Establishment

4.1.1 Coordinate representation in the spatial coordinate system

Based on the model establishment, since UAV FY1 needs to release 3 smoke interference bombs in, additional time variables need to be introduced to represent the motion trajectories of the other two smoke clouds. Let the center coordinates of the second smoke cloud be represented by time variables t_3 and t_4 , and the center coordinates of the third smoke cloud be represented by time variables t_5 and t_6 . The specific expressions are as follows:

The center coordinates (R_{w2}, U_{w2}, G_{w2}) of the second smoke cloud are expressed as (for $t \geq t_3 + t_4$):

$$\begin{cases} R_{w2} = 17800 + v \cos[\dot{\theta}_0] \alpha_4 t_3 \\ U_{w2} = v \sin[\dot{\theta}_0] \alpha_4 t_3 \\ G_{w2} = 1800 - 4.9 t_4^2 - 3(t - t_3 - t_4) \end{cases} \quad (18)$$

The center coordinates (R_{w3}, U_{w3}, G_{w3}) of the third smoke cloud are expressed as (for $t \geq t_5 + t_6$):

$$\begin{cases} R_{w3} = 17800 + v \cos[\dot{\theta}_0] \alpha_4 t_5 \\ U_{w3} = v \sin[\dot{\theta}_0] \alpha_4 t_5 \\ G_{w3} = 1800 - 4.9 t_6^2 - 3(t - t_5 - t_6) \end{cases} \quad (19)$$

4.1.2 Judgment of multi-smoke composite shielding

Since UAV FY1 will release 3 smoke interference bombs, there may be scenarios where two or more smoke clouds act together to achieve effective shielding. To evaluate the composite shielding effect, the surface of the real target cylinder is discretized into uniform small cells, and the center coordinates of each cell are used to represent its position.

Through sampling detection, it is determined whether the smoke clouds achieve effective shielding. If some cells are effectively shielded by one smoke cloud and the other cells are effectively shielded by another smoke cloud, and the union of the two parts of cells covers all cells, then the smoke clouds are considered to have achieved effective shielding.

From this, the judgment function $I(t)$ for whether the real target is completely shielded at time t can be derived.

Thus, the objective function is:

$$\max \int_{t_1+t_2}^{t_1+t_2+20} N(t)dt \quad (19)$$

$$N(t) = \begin{cases} 1, & \text{Effective shielding at time } t, \\ 0, & \text{Otherwise.} \end{cases} \quad (20)$$

The constraint conditions are:

$t_3 - t_1 \geq 1$ (Minimum time interval between the release of the first and second smoke bombs),

$t_5 - t_3 \geq 1$ (Minimum time interval between the release of the second and third smoke bombs).

4.2 Model Solution and Result Analysis

4.2.1 Algorithm design

Algorithm 3: Basin-Hopping Particle Swarm Optimization Algorithm

Objective: Design a strategy for FY1 to release 3 smoke interference bombs and solve the maximum effective shielding time.

Determine Optimization Variables: Identify the release angle α_4 , flight speed v of the UAV, and each release time node and detonation time node of the smoke interference bombs.

Generate Initial Particles: Randomly generate initial values of optimization variables within their respective ranges, ensuring that the time interval constraints between releases are satisfied.

Fitness Calculation (Total Effective Shielding Time): For each particle, analyze the entire motion process, calculate the smoke trajectory, traverse the missile trajectory at time steps, determine whether the smoke clouds effectively shield the missile, and count the total shielding time and the individual shielding time of each smoke cloud.

Search for the Optimal Solution Based on PSO: Update particle positions and speeds according to PSO rules, and iterate to find the local optimal solution.

Restart Basin-Hopping: When PSO converges to a local optimal solution, perturb the global optimal solution to jump out of the local optimum, and restart PSO with the new solution as the initial point.

Output Results: After multiple basin-hopping restarts and PSO iterations, output the global optimal solution and the corresponding maximum effective shielding time.

4.2.2 Model solution and result analysis

Based on Algorithm 3, programming is implemented in MATLAB, and the solution results are shown in the following Table 3:

Table 3 Optimal Solution Results

Flight Direction Angle of FY1	4.7643° (with the positive x-axis as the reference, counterclockwise as the positive direction)
Flight Speed of FY1	115.63 m/s
Release Point of Smoke Interference Bomb 1	(17800, 0, 1800)
Detonation Point of Smoke Interference Bomb 1	(17812, 0.2053, 1799.951)
Release Point of Smoke Interference Bomb 2	(17919, 2.0526, 1800)
Detonation Point of Smoke Interference Bomb 2	(17931, 2.2578, 1799.951)
Release Point of Smoke Interference Bomb 3	(18994, 20.5256, 1800)
Detonation Point of Smoke Interference Bomb 3	(19005, 20.7308, 1799.951)
Maximum Effective Shielding Time	6.302 s

5 CONCLUSIONS

This study successfully established a geometric-physical model describing the process of drone smoke interference against missiles, employing either the conical angle method or distance determination method to precisely quantify the effective obfuscation effect of smoke clouds on cylindrical real targets. By applying different optimization algorithms, this study achieved significant maximization of effective concealment duration:

1. In calculating effective concealment duration for a single smoke grenade, based on initial parameters, the effective concealment duration of the smoke grenade for M1 was 1.391975s.
2. For the optimal deployment strategy of a single drone with a single flare, hybrid optimization using genetic algorithms and particle swarm optimization increased the maximum effective concealment time to 4.585 seconds.
3. For coordinated multi-flare concealment optimization by a single drone, the basin hopping-particle swarm optimization algorithm achieved a maximum composite effective concealment time of 6.3020 seconds.

In summary, this study demonstrates that multi-variable optimization of key parameters—including drone flight direction, velocity, and smoke grenade deployment timing—enables hybrid optimization strategies (e.g., GA-PSO and

Basin Jumping-PSO) to effectively address complex nonlinear problems. This provides a quantifiable and actionable solution for achieving maximum effective shielding under coordinated interference from a single drone deploying multiple smoke grenades.

Future research may further explore multi-UAV cooperative smoke deployment strategies under complex battlefield conditions, incorporating real-time environmental factors such as wind field variations and atmospheric stability. In addition, integrating machine learning for adaptive decision-making represents a promising direction for enhancing response speed and robustness in dynamic scenarios.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

- [1] Huang Na, Niu Xinglin, Luo Zhengyou, et al. Research on Manufacturing and Performance Optimization of Smoke Disturbance Grenades in Special Ammunition. *China Military-Civilian Conversion*, 2025(09): 22-23.
- [2] Huang Na, Luo Zhengyou, Niu Xinglin, et al. Research and Development of Novel Materials for Smoke Distraction Grenades. *China Military-Civilian Conversion*, 2025(08): 27-28.
- [3] Luan Yongchao, Zhang Bin, Li Chenkai, et al. Method for Measuring Muzzle Bullet Velocity Under Heavy Smoke Interference. *Journal of Ordnance Engineering*, 2025, 46(03): 191-201.
- [4] Luan Yongchao, Zhang Bin, Li Chenkai, et al. Method for Measuring Muzzle Projectile Initial Velocity Under Strong Smoke Interference. *Journal of Ordnance Engineering*, 2025: 1-11.
- [5] Zhang Jun, Leng Zhihui, Xu Lei, et al. Application Research of Smoke Disruption Pods on a Certain Aircraft Model for Aerial Disruption. *Trainer Aircraft*, 2023(01): 16-19.
- [6] Yang D Y, Qiu X B, Li C L, et al. Rapid Algorithm for Mie Scattering Coefficient in Smoke-Induced Interference of Optically Guided Weapons. *Firepower and Command Control*, 2017, 42(08): 56-60.
- [7] Lei Dan. Research on Video-Based Smoke Detection Methods for Highway Tunnels. Dalian Maritime University, 2017.
- [8] Zhang Xinyue. Signal Processing Technology for DSP-Based Frequency-Modulated Continuous Wave Laser Ranging. Beijing Institute of Technology, 2016.
- [9] Jia B H, Feng Y, Jia W H. Application of dual-ring coaxial fiber optic sensors in blade tip clearance measurement. *Advances in Lasers and Optoelectronics*, 2015, 52(10): 91-97.
- [10] Chen Zhibin, Zhang Chao, Song Yan, et al. Application of Gray-Scale Stretch Retinex in Smoke Image Enhancement with Large Dynamic Range. *Infrared and Laser Engineering*, 2014, 43(09): 3146-3150.