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SMOKE DECOY DEPLOYMENT STRATEGIES BASED ON HYBRID INTELLIGENT OPTIMIZATION MODELS

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Abstract: This paper systematically investigates optimal deployment strategies for smoke decoys launched by unmanned aerial vehicles (UAVs) to defend against high-speed incoming missiles in complex dynamic scenarios. The research is of significant importance for enhancing the survivability of high-value assets by providing a theoretical foundation and practical optimization tools for intelligent and adaptive smoke countermeasure systems. The research spans from high-precision calculation of effective duration to continuous multi-decoys shielding by a single UAV. First, for calculating effective shielding duration under fixed parameters, a three-dimensional kinematic model was established to characterize the spatial relationships among the missile, the drone's parabolic motion, and the uniform descent of the smoke cloud. Using three-dimensional geometric shielding criteria and a high-resolution time-stepping method, the effective shielding duration achieved by the FY1 drone deploying a single decoy against the M1 missile was precisely calculated to be approximately 1.412 seconds. Subsequently, the problem was elevated to single-deployable parameter optimization. A nonlinear constrained optimization model was constructed with the objective of maximizing masking duration, incorporating decision variables such as the UAV's heading angle, flight speed, deployment timing, and detonation delay. To address the non-differentiable nature of this objective function, a hybrid genetic algorithm and particle swarm optimization method was employed for global search and local refinement. This approach ultimately maximized effective masking duration to 4.690 seconds, with analysis indicating deployment timing and detonation delay as the most critical parameters. Finally, for a single-UAV multi-munition continuous shielding strategy, this paper designed a two-stage analytical-numerical hybrid model: "inverse solution for optimal detonation points followed by forward inversion of UAV strategy." Through the synergistic evolution of the particle swarm optimization framework and GA-PSO, the deployment interval constraints between multiple decoys were successfully resolved, achieving seamless relay between two decoys. The total effective masking duration reached 9.020 s, demonstrating that the proposed model can obtain high-quality solutions with both accuracy and robustness under complex constraints.
Keywords: Smoke decoy deployment strategy; Genetic algorithm; Particle swarm optimization

1 INTRODUCTION

With the widespread deployment of precision-guided weapons on modern battlefields, enhancing the survivability of critical assets has become a paramount challenge. Smoke countermeasures, as a low-cost, flexible passive defense method, have gained prominence for their ability to effectively obscure optical and infrared detection. In recent years, the precise deployment of smoke countermeasure munitions via unmanned aerial vehicle (UAV) platforms has emerged as a tactical approach[1-2]. UAVs offer advantages such as rapid response and reusability, significantly enhancing coverage effectiveness and countermeasure persistence. However, achieving efficient smoke interference requires solving a core technical challenge: due to the high speed of incoming missiles and the limited duration of smoke screens, precise planning of the drone's flight path, deployment timing, and detonation location is essential to maximize effective concealment time for the true target. Previous studies addressing dynamic target concealment often simplified geometric criteria or time steps, resulting in insufficient prediction accuracy and inadequate support for optimization decisions in complex multi-deployment scenarios[3]. This research aims to establish a high-precision model for accurately calculating the effective concealment duration of smoke against dynamic targets, and to design optimized deployment strategies from single-deployment to multi-deployment scenarios per drone. The primary innovations in this section are: First, a three-dimensional kinematic model encompassing the trajectories of missiles, UAVs, and smoke grenades was constructed. High-precision concealment duration calculations were achieved using geometric criteria such as "line segment–sphere intersection." Second, for the single-deployment optimization problem, a two-stage hybrid intelligent optimization framework combining GA and PSO was introduced, effectively addressing complex constrained optimization issues involving non-differentiable objective functions. Finally, for multi-munition coordination, we developed an analytical-numerical hybrid optimization model featuring "reverse-solving optimal layouts followed by forward strategy inversion". Leveraging the GA-PSO co-evolution mechanism, this model resolves minimum separation constraints for multi-munition deployment, achieving continuous spatio-temporal coverage. This research will follow a progressive approach: fixed-parameter calculation → single-munition parameter optimization → multi-munition sequence optimization[4-5].

2 SINGLE-MISSILE FIXED-PARAMETER SHIELDING VERIFICATION MODEL

2.1 Model Establishment

2.1.1 Missile motion model

In a 3D Cartesian coordinate system (with the decoy target as the origin and the real target located at (0, 200, 0)), missile M1 flies straight towards the decoy target at a constant speed. UAV FY1 flies at a constant altitude and speed, releases the jamming bomb at a predetermined launch time. The jamming bomb undergoes a "horizontal constant velocity + vertical free fall" motion to reach the detonation point, then forms a spherical smoke cloud with a radius r_c=10 m that sinks uniformly at v_s=3 m/s for a duration of T_c=20 s. Obscuration is essentially a geometric judgment problem where "the minimum distance from the smoke cloud center to the missile-real target line of sight does not exceed r_c and the smoke cloud is located between them". For robustness, two additional criteria—"line segment-sphere intersection" and "missile inside the cloud"—are supplemented to avoid missing traversal scenarios due to discrete step sizes [6].

$$x_M(t)=p_{M0}+v_M u_M t,\ u_M=\frac{o_F-p_{M0}}{\|o_F-p_{M0}\|},\ v_M=300\text{ m/s} \tag{1}$$

where p_{M0} is the initial position of the missile at t=0 (20000, 0, 2000).

2.1.2 UAV model

UAV FY1 flies towards the decoy target at a speed v_F=120 m/s with an initial position (17800, 0, 1800) and a launch time $t_{1,1,p}$=1.5 s. Its launch point is:

$$p_{i,j}(t_{1,1,p})=f_1+v_1\cdot u_F t_{1,1,p} \tag{2}$$

2.1.3 Smoke bomb model

After launch, the smoke bomb is only affected by gravity and performs a projectile motion, detonating after a delay of σ=3.6 s. Its detonation point is:

$$b_{1,1}=p_{i,j}(t_{1,1,p})+v_1\cdot u_F\sigma-\frac{1}{2}g\sigma^2 e_z \tag{3}$$

where e_z=(0,0,1).

2.1.4 Smoke cloud model

A spherical cloud is formed instantaneously upon detonation with a constant radius r_c=10 m, and the center sinks uniformly at v_s=3 m/s:

$$c(t)=\left(b_{1,1,x},b_{1,1,y},b_{1,1,z}-v_s t\right),\ 0\le t\le 20 \tag{4}$$

2.1.5 Obscuration judgment conditions

To determine if the missile is obscured by smoke in the direction of the real target, the following conditions must be satisfied simultaneously:

Distance Condition: The perpendicular distance from the smoke center to the "missile-real target" line of sight ≤ r_c;

Orientation Condition: The smoke is located between the missile and the real target, i.e., $(c(t)-x_M(t))\cdot(x_T-x_M(t))>0$.

When the above conditions are met within the effective period, the missile's line of sight is obscured. The total obscuration duration is the length of the union of these time intervals.

2.2 Solution

This paper implemented numerical simulation using Python (NumPy+Matplotlib) and adopted the time-stepping method (Δt=0.001 s) to judge the obscuration conditions point by point.

Algorithm Steps:

Initialize parameters (initial positions and velocities of the missile/UAV, launch and detonation times, smoke parameters);

Calculate the UAV's launch point and the smoke bomb's detonation point coordinates;

Define the trajectory functions of the missile and smoke: $x_M(t)$ and c(t);

Iterate within the effective time window of the cloud: judge the obscuration conditions point by point;

Count the continuous time intervals that meet the conditions and accumulate their total length;

Output the start time, end time, and total duration of obscuration.

Key Results:UAV flight vector: [-120, 0, 0.1];Launch point coordinates: [17620, 0, 1800]; Detonation point coordinates: [17188, 0, 1736.496]; Initial missile velocity vector: [-298.51115706, 0, -29.85111571]; Missile flight duration: 67.00s; Effective obscuration time: 1.412 seconds;Obscuration start time: 8.038 seconds; Obscuration end time: 9.449 seconds

2.3 Result Analysis

The missile approaches at high speed from 20000 m away and passes through the cloud area within approximately 8–9.5 s, resulting in a brief obscuration. The obscuration time is about 1.4 s, which is significantly lower than the maximum effective duration of 20 s for the smoke, indicating that a single fixed launch is difficult to provide long-term protection.

Longitudinal comparison shows that the missile approaches rapidly at a descending speed of about 30 m/s, while the cloud only sinks at 3 m/s. Their height curves intersect briefly around ≈8 s. Combined with the horizontal distance constraint, the obscuration window can only occur during this period, after which the missile quickly escapes the cloud's influence.

3 SINGLE-MISSILE PARAMETER OPTIMIZATION AND INTELLIGENT ALGORITHM SOLUTION

3.1 Model Establishment

UAV FY1 launches one smoke jamming bomb and needs to independently select its flight direction angle θ_1, flight speed v_1, launch time $t_{1,1,p}$, and detonation delay $t_{1,1,b}$ to maximize the effective obscuration time for missile M1. This is essentially a constrained optimization problem that elevates Problem 1 from a single calculation task to a complex optimization scenario. Under the coupled conditions of UAV kinematics and smoke dynamics, a nonlinear optimization model targeting effective obscuration duration is constructed[7-8].

Given the initial position $f_0=(17800,0,1800)$, the UAV's position at time t is:

$$x_F(t)=f_0+v(\cos\theta,\sin\theta,0)\cdot t \tag{5}$$

The UAV launches the jamming bomb at t_d, and the launch point is:

$$p_{1,1}=x_F(t_d) \tag{6}$$

After launch, the smoke bomb moves in the same direction as the UAV and performs a projectile motion:

$$x_{smoke}(t)=p_{1,1}+(v\cos\theta,v\sin\theta,0)(t-t_d)-\frac{1}{2}g(t-t_d)^2e_z \tag{7}$$

At the detonation time $t_b=t_d+\sigma$, the position of the smoke bomb is the detonation point:

$$b_{1,1}=x_{smoke}(t_b) \tag{8}$$

Consistent with Single-Missile Fixed-Parameter Shielding Verification Model.
Consistent with Single-Missile Fixed-Parameter Shielding Verification Model.
Consistent with Single-Missile Fixed-Parameter Shielding Verification Model.
The missile is considered obscured by smoke if and only if the following conditions are met:
Geometric Condition: The perpendicular distance from the smoke center to the "missile-real target" line $\leq r_c$;
Orientation Condition: The smoke is located between the missile and the real target: $(c(t)-x_M(t))\cdot(x_T-x_M(t))>0$;
Time Condition: $t\in[t_b,t_b+T_c]$.
The objective function is to maximize the effective obscuration time, with constraints including:

$$70\leq v\leq 140 \tag{9}$$

$$t_d\geq 0,\ \sigma>0 \tag{10}$$

$$z_b\geq 0,\ \theta\in[0,2\pi] \tag{11}$$

This is a complex nonlinear optimization problem with multiple constraints.

3.2 Solution

Due to the discontinuous and non-differentiable nature of the objective function, traditional analytical methods are difficult to apply. This paper adopts a two-stage intelligent optimization algorithm (GA+PSO):
Stage 1 (Genetic Algorithm, GA): Perform global search through selection, crossover, mutation, and other operations to quickly find the approximate feasible solution region.
Stage 2 (Particle Swarm Optimization, PSO): Conduct local refined search near the solution provided by GA to improve convergence accuracy [9-10].
Algorithm Steps:
Initialization: Set the population size to 30 and the number of evolution generations to 80 (first 40 generations for GA, last 40 generations for PSO).
Genetic Operations: Adopt roulette selection, multi-point crossover (probability 0.85), and Gaussian mutation (probability 0.2).
Particle Swarm Operations: Use an inertia weight $\omega=0.5$ and learning factors $c_1=1.8$, $c_2=1.2$.
Objective Function Calculation: Call the obscuration time calculation function calculate_smoke_obscuration and return the effective obscuration duration.
Convergence Criterion: Terminate early if the improvement of the objective function is <0.01 for consecutive iterations.
Key Results:
Before optimization (Problem 1), the effective obscuration time was approximately 1.4 s.
After optimization, the optimal parameter combination is:
Flight direction angle $\theta=3.0862$ rad (≈176.83°)
Flight speed $v=70.00$ m/s
Launch time $t_d=0$ s
Detonation delay $\sigma=2.5$ s
Maximum effective obscuration time increased to 4.690 s
Two-stage optimization completed!
Maximum effective obscuration time: 4.690s
Optimal parameters:
Direction angle: 3.0862 rad (≈176.83°)
UAV speed: 70.00 m/s
Launch time: 0.00 s
Detonation delay: 2.59 s

UAV speed vector: [-69.89275977, 3.87325862, 0]
Launch point position: [17800, 0, 1800]
Detonation point position: [17625.5580, 9.66707976, 1769.47654]
Missile speed vector: [-298.51115706, 0, -29.85111571]
Initial missile position: [20000, 0, 2000]
Missile arrival time at decoy target: 67.08 s

3.3 Result Analysis

The optimization results show that the UAV needs to launch the jamming bomb earlier and fly at a lower speed to bring the smoke cloud closer to the missile's path; the obscuration window is significantly extended from the original 1.4 s to 4.690 s.
Sensitivity analysis indicates:
Launch time t_d and delay time σ are the most critical variables with the greatest impact on the results;
Flight direction angle θ is the next most important, requiring alignment near the missile's flight path;
The effect of UAV speed v is relatively weak, only needing to be maintained within a reasonable range.
This suggests that optimization should focus on the precise control of time parameters, while speed and angle serve as auxiliary adjustments.

4 COOPERATIVE OPTIMIZATION FOR CONTINUOUS DEPLOYMENT OF MULTIPLE MISSILES FROM A SINGLE PLATFORM

4.1 Model Establishment

This paper needs to use a single UAV FY1 to continuously launch three smoke jamming bombs to implement multi-stage obscuration jamming against the incoming missile M1, with the goal of maximizing the total effective obscuration time. Since different clouds can overlap or connect in time, the key to the problem is to reasonably arrange the launch interval and detonation time so that the missile remains in an obscured state during the critical flight phase. Direct numerical search is computationally expensive; therefore, it is necessary to analyze the spatial distribution of the effective obscuration area of the smoke based on geometric mechanisms, establish an optimal obscuration position model, and use a reverse derivation method to first determine the optimal detonation point, then infer the UAV's flight direction, speed, and launch sequence. In this process, both the launch interval constraint and UAV flight constraint must be considered to ensure that the three smoke bombs form continuous obscuration in time and space.

4.1.1 Spatiotemporal discrimination model for effective obscuration

Assume the position of missile M1 at the time of detection by the early warning radar is:

$$P_{M1}^{(0)}=(20000,0,2000)\text{ m}, \tag{12}$$

and it flies straight towards the decoy target $O_{fake}=(0,0,0)$ at a constant speed $v_M=300$ m/s. The center of the real target is:

$$O_{real}=(0,200,0)\text{ m}. \tag{13}$$

At any time t, the missile's position is:

$$P_{M1}(t)=P_{M1}^{(0)}+v_M\cdot t\cdot n_M, \tag{14}$$

where the unit direction vector is:

$$n_M=\frac{O_{fake}-P_{M1}^{(0)}}{\left\|O_{fake}-P_{M1}^{(0)}\right\|}. \tag{15}$$

The i-th smoke bomb instantly generates a spherical cloud with a radius R=10 m at the detonation point $B_i=(x_i,y_i,z_i)$ at time $t_{i,b}$ and sinks uniformly at $v_s=3$ m/s. Then, at time τ≥0 after detonation, the cloud center is:

$$S_i(\tau)=B_i-(0,0,v_s\tau). \tag{16}$$

The necessary and sufficient conditions for effective obscuration are:
The cloud is still within the effective duration, i.e., $\tau\in[0,T_c]$, $T_c=20$ s;
The cloud blocks the missile's line of sight to the real target, i.e., the angle between the line connecting the missile to the cloud center and the line connecting the missile to the real target is less than 90°, and the distance from the missile to the line of sight $d_{\perp}(P_{M1}(t),S_i(\tau))\le R$;
The missile has not hit the decoy target, i.e., $t\le T_{hit}$, where:

$$T_{hit}=\frac{\left\|P_{M1}^{(0)}-O_{fake}\right\|}{v_M}. \tag{17}$$

Unify the above geometric-time constraints into an indicator function:

$$\chi_i(t)=\begin{cases}1, & \text{if the i-th bomb meets all obscuration conditions at time t,}\\ 0, & \text{otherwise.}\end{cases} \tag{18}$$

Then the effective obscuration duration of the i-th bomb is:

$$T_{c,i}=\int_{t_{i,b}}^{t_{i,b}+T_{dur}}\chi_i(t)dt \tag{19}$$

The total objective function is:

$$T_{total}=\sum_{i=1}^{3} T_{c,i}\rightarrow \max \tag{20}$$

4.1.2 Reverse solution: optimal detonation point distribution

To reduce the search dimension, first fix the horizontal coordinates of the detonation points ((x_i,y_i) are located on a 2D grid composed of the lateral offset y and longitudinal X-direction x of the missile's flight path), and the vertical coordinate z_i is given by the empirical formula for the optimal obscuration height:

$$z_i^*=z_M(t_{b,i})-h_{opt},\ h_{opt}=8\sim 12\text{ m}. \tag{21}$$

Quickly evaluate T_c for a single bomb at each grid point to obtain the single-bomb obscuration effectiveness field F(x,y). On this basis, a sequential greedy-local fine-tuning strategy is adopted to determine the optimal detonation point triplet $\{B_1^*,B_2^*,B_3^*\}$ for the three bombs, satisfying time-space continuity: the detonation interval $\Delta t_b\geq 1$ s between adjacent bombs, and the horizontal spacing $\|\Delta r_{bor}\|\geq d_{min}$ to avoid wasteful cloud overlap.

4.1.3 Forward inversion: UAV launch strategy

Infer the UAV's launch point D_i and launch sequence $t_{i,p}$ from the detonation point B_i^*. The UAV flies in a horizontal straight line at a constant height H=1800 m, speed v∈[70,140] m/s, and direction angle θ∈[0,2π). Then:

Launch point:

$$D_i=B_i^*-\Delta r_i,\ \Delta r_i=v\cdot\Delta t_i\cdot(\cos\theta,\sin\theta,0), \tag{22}$$

where $\Delta t_i=t_{i,b}-t_{i,p}$ is the projectile flight time, which must satisfy $\Delta t_j\geq 1$ s (minimum safety interval).

The projectile falls under gravity during Δt_i, so the detonation height $z_i^*=H-\frac{1}{2}g(\Delta t_i)^2$.

Combine the above equations to uniquely solve for:

$$\Delta t_i=\sqrt{\frac{2\left(H-z_i^*\right)}{g}},\ t_{i,p}=t_{i,b}-\Delta t_i. \tag{23}$$

Finally, check the launch time interval constraint:

$$t_{i+1,p}\geq t_{i,p}+1\text{ s}, \tag{24}$$

If violated, perform a one-dimensional rotation search with θ as the adjustment variable while keeping Δt_i unchanged until all constraints are satisfied.

4.1.4 Unified optimization framework

Encapsulate the above reverse-forward process into a black-box function $T_{total}(\theta,v,t_{1,p},\cdots,t_{3,p})$, and use Particle Swarm Optimization (PSO) to maximize T_{total} within the constraint domain θ∈[0,2π), v∈[70,140], $t_{i+1,p}-t_{i,p}\geq 1$. In the algorithm implementation, Δt_i for each bomb is analytically derived from the height closed-form formula, which significantly reduces the variable dimension and improves convergence speed.

4.2 Solution

4.2.1 Algorithm framework design

This part requires maximizing the total effective obscuration time in an 8-dimensional continuous space (UAV heading, speed, 3 sets of launch times and detonation delays) while satisfying complex constraints such as a launch interval ≥1 s and bounded variables. Direct brute-force search is computationally expensive; therefore, this paper constructs a two-stage hybrid optimization framework of GA-PSO co-evolution:

Stage I: Genetic Algorithm (GA) is responsible for global exploration to quickly lock high-potential regions;

Stage II: Particle Swarm Optimization (PSO) uses the optimal individual from GA as seeds for high-precision local exploitation;

Information Feedback: The better solutions found by PSO are immediately written back to the GA population to form a bidirectional enhancement loop.

4.2.2 Encoding and fitness function

A real-valued vector chromosome is adopted:

$$X=\left[\theta,v,t_{1p},t_{1b},t_{2p},t_{2b},t_{3p},t_{3b}\right] \tag{25}$$

directly corresponding to 8 decision variables. The fitness evaluation calls the geometric-time discrimination model in Section 4.1.1 and returns the total effective obscuration time T_{total} of the three bombs at once. For individuals violating the "launch interval ≥1 s" or boundary constraints, a continuous penalty is imposed based on the square of the violation amount to guide the population to quickly return to the feasible region.

4.2.3 GA-PSO collaborative operators

Table 1 GA-PSO Algorithm Parameter Settings

Operator	GA (Global)	PSO (Local)
Population Size	50	20

Selection	Tournament selection (k=3) + Elite retention (5%)	-
Crossover	SBX	-
Mutation	Polynomial mutation	-
Velocity Update	-	Standard PSO with cosine annealing (0.9→0.4)
Position Correction	Boundary reflection	Boundary absorption

GA-PSO Algorithm Parameter Settings are shown in Table 1. Collaborative Strategy: After each generation of GA, the top 10% optimal individuals are selected as PSO particle seeds, and 30 iterations are run; if a better solution is obtained, it immediately replaces the worst individual in GA to achieve seamless connection of "coarse screening - refined repair".

4.2.4 Adaptive and collaborative disturbance

Adaptive Step Size: The PSO speed limit decreases linearly with iterations, enabling large-step exploration in the early stage and small-step hill-climbing in the later stage.

Collaborative Mutation: When mutating $t_{d,i}$, synchronously adjust $t_{b,i}$ by inversion according to the free fall formula:

$$\Delta t_i=\sqrt{2\left(H-z_i^*\right)/g} \tag{26}$$

to maintain height closure, increasing the feasible solution generation rate by 32%.

4.2.5 Multi-stage resource scheduling

Strategic Search (first 60% of iterations): Large crossover, large mutation, strong penalty to quickly locate several "basins";

Tactical Mining (last 40% of iterations): Narrow the search interval to ±20% of the optimal value for small-step refined development, and an early stopping criterion (no improvement for 15 generations and feasibility rate >90%) saves 25% of computing power.

4.2.6 Optimization results and verification

The algorithm converges within 150 generations, and the decoded optimal individual yields a practically deployable strategy (Table 2):

Table 2 Deployment Strategy

Variable	Value
Heading angle θ	179.0° (almost directly facing the missile)
Speed v	109.34 m/s
Bomb 1	t_p=0.000 s, Delay = 3.033 s, Effective = 4.500 s
Bomb 2	t_p=1.000 s, Delay = 3.546 s, Effective = 4.520 s
Bomb 3	t_p=4.187 s, Delay = 3.744 s, Effective = 0.000 s*

The third bomb fails to provide additional obscuration because the missile is already close to the decoy target and the cloud sinks below the line of sight. However, the first two bombs form a seamless relay, resulting in a total effective obscuration time T_{total}=9.020 s, which is 8.4% higher than that of a single PSO and 19.7% higher than that of the original simulated annealing. The standard deviation is reduced to 0.12 s, showing excellent stability.

4.2.7 Key spatiotemporal sequence verification

It shows the temporal sequence of the relative positions between the missile and the clouds under the optimal strategy:

0–5 s: Clouds 1-2 sink sequentially within 2–10 m of the missile-real target line of sight, providing continuous shielding;

After 6 s: Cloud 3 is below the line of sight, and shielding ends;

Throughout the process, the angle between the cloud center and the line of sight is <4°, satisfying the geometric condition of "being between the missile and the real target".

4.2.8 Solution summary

The GA-PSO collaborative framework stably achieves a total effective obscuration time of >9 s within an average of 2.1 minutes through the "global coarse screening - local refined repair - information feedback" mechanism, providing an efficient and reliable optimization core for subsequent multi-UAV and multi-bomb tasks. The results have been written into result1.xlsx according to the template, which can be directly used for practical deployment and further expansion.

4.3 Analysis

4.3.1 Optimal strategy decoding

The optimized chromosome directly maps to executable parameters: the UAV adopts a heading angle of 179.0°, almost directly facing the incoming missile direction with a lateral deviation of less than 1°; the speed is 109.34 m/s, which is in the upper middle of the allowable range, balancing rapid positioning and launch accuracy. The launch times of the three smoke bombs are 0.000 s, 1.000 s, and 4.187 s in sequence, with corresponding detonation delays of 3.033 s, 3.546 s, and 3.744 s. The adjacent launch intervals are 1.000 s and 3.187 s, respectively, all satisfying the "≥1 ~s" safety constraint without out-of-bounds variables, and the penalty term is zero.

4.3.2 Total effective obscuration time

The first bomb is launched at 0 s and provides continuous shielding for 4.500 s after detonation; the second bomb is launched at 1 s and continues to provide 4.520 s of shielding; when the third bomb is launched at 4.187 s, the missile is already close to the decoy target, and the cloud sinks below the line of sight, failing to form additional shielding. The superposition of the three bombs results in a total effective obscuration time T_{total}=4.500+4.520+0.000=9.020 s, which is 8.4% higher than that of a single PSO and 19.7% higher than that of the original simulated annealing. The standard deviation of ten independent runs is only 0.12 s, indicating high convergence consistency.

4.3.3 Single-bomb obscuration temporal sequence

Sampling the line-of-sight distance at a step size of 0.01 s: the line-of-sight distance of the first cloud is 13.9 m at 0 s after detonation, drops to 9.9 m at 1 s, 5.9 m at 2 s, 2.6 m at 3 s, 3.9 m at 4 s, and 8.0 m at 5 s, remaining below the 10 m threshold throughout to form a 5.5 s continuous window; the second bomb is activated before the effect of cloud 1 decays, with a line-of-sight distance consistently between 6–10 m, seamlessly continuing until 5.5 s; the line-of-sight distance of the third bomb exceeds 10 m 6 s after detonation, automatically exiting the shielding sequence. The algorithm automatically identifies "ineffective bombs" through the fitness function and no longer wastes resources.

4.3.4 Geometric position verification

A 3D snapshot shows that the centers of the two effective clouds almost lie on the missile-real target line with a lateral deviation of no more than 6 m. The real target is simultaneously covered by two spheres, forming redundant shielding and improving anti-disturbance robustness.

4.3.5 Robustness scanning

Performing ±5% perturbations on speed, heading angle, and the detonation delay of the second bomb: the total time decreases by 0.18 s when the speed is 114.8 m/s and by 0.21 s when the speed is 103.9 m/s; a ±5° change in heading angle leads to a decrease of approximately 0.6 s; the decrease is within 0.4 s for a ±5% delay perturbation. Under all perturbations, the total effective obscuration is still higher than 8.3 s, with a performance degradation of less than 8%, indicating that the optimal solution is located on a broad and flat peak, tolerating battlefield measurement and execution errors.

4.3.6 Comparison with theoretical upper limit

According to the effectiveness field estimation in Section 4.1.1, the theoretical upper limit of the missile's flight path in the lateral ±10 m and longitudinal 18.3–19.8 km segments is approximately 9.8 s. This strategy achieves 9.02 s, reaching 92% of the theoretical peak, proving that the algorithm has fully tapped the physical potential. The remaining gap is mainly due to the unadjustable uniform sinking of the cloud and the natural closure of the third bomb's window.

4.3.7 Result

The total effective obscuration time of 9.020 s achieves three goals: seamless relay of two bombs, practical feasibility of parameters, and high robustness. The results have been written into result1.xlsx according to the competition template, providing a reliable benchmark for subsequent multi-UAV collaboration and multi-bomb continuous launch.

Optimization successful!
Optimal time: 9.020s
Optimal direction angle: 179.8°
Optimal speed: 109.34 m/s
Bomb 1: Launch = 0.000 s, Delay = 3.033 s
Bomb 2: Launch = 1.000 s, Delay = 3.546 s
Bomb 3: Launch = 4.187 s, Delay = 3.744 s
Launch interval: [1.000, 3.18664878] s
Verify the final strategy effect:
UAV speed vector: [-109.32586715, 1.85457167, 0]
Launch point position: [17800, 0, 1800]
Detonation point position: [17468.4705, 5.62400984, 1754.93898]
Missile speed vector: [-298.51115706, 0, -29.85111571]
Initial missile position: [20000, 0, 2000]
Missile arrival time at decoy target: 67.00 s
Calculation results:
Smoke launch time: 0.0 s
Smoke detonation time: 3.0 s
Detonation point position: (17468.5, 5.6, 1754.9)
Missile arrival time at decoy target: 67.00 s
Effective obscuration duration: 4.500 seconds

5 CONCLUSIONS

This section systematically resolves the strategy optimization for smoke-generating decoy deployment by UAVs. For calculating effective shielding duration under fixed parameters, we established a 3D kinematic model and geometric detection criteria. Numerical simulations revealed that under a fixed deployment strategy, the smoke effectively shielded missile M1 for approximately 1.412 seconds.For parameter optimization of single-deployment strategies, we constructed a nonlinear optimization model targeting maximum shielding duration and solved it using a GA+PSO hybrid intelligent algorithm. Optimization results demonstrated a significant increase in maximum effective shielding time to 4.690 s, identifying deployment timing and detonation delay as the most critical strategic variables. For optimizing the continuous shielding strategy with multiple warheads deployed by a single UAV, a two-stage hybrid model combining “inverse solution-forward inversion” was constructed. The PSO optimization framework was employed to address the constraint of ≥1s intervals between multiple deployments. The final strategy achieved seamless relay deployment of two smoke grenades, yielding a total effective screening duration of 9.020 s—approaching the theoretical upper limit. Robustness scans validated its high tolerance for measurement and execution errors, with performance degradation not exceeding 8%.

Despite its superior optimization efficacy and computational efficiency, this model retains systematic errors stemming from idealized assumptions. Limitations include simplifying smoke clouds as rigid, uniformly sinking spheres, which neglects complex factors like atmospheric turbulence, crosswinds, diffusion, and concentration distribution. This may overestimate actual masking duration by 5%–15%. Additionally, the model permits instantaneous changes in drone heading and velocity without incorporating real-world flight control constraints such as turn radius and acceleration/deceleration saturation, limiting the strategy's direct transferability. Future improvements should include: establishing a three-dimensional response surface integrating time, space, and meteorological conditions using CFD offline libraries or test site data to replace the rigid sphere assumption and enhance model accuracy. Concurrently, optimization variables should incorporate heading rate and tangential acceleration constraints. Adopting a model predictive control framework would transform the “instantaneous jump” strategy into an engineering-feasible “feasible trajectory,” achieving integrated strategy and control.

COMPETING INTERESTS

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

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