

Research on an Optimized Model for Drone Decoy Jammer Shielding Based on Particle Swarm Optimization Algorithm and Two-Stage Decomposition Algorithm

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Abstract. This paper proposes a shielding optimization model for smoke decoy deployment by unmanned aerial vehicles (UAVs) and a particle swarm optimization (PSO) algorithm solution. It focuses on exploring model construction and PSO algorithm application effectiveness under different UAV and smoke decoy configurations. First, for a scenario involving a single UAV releasing one smoke grenade, a model is constructed with the objective of maximizing shielding duration. Decision variables and constraints—including velocity vectors and detonation point locations—are defined. After 25 iterations, the PSO algorithm converges to an optimal or locally optimal solution. Second, for a scenario involving a single UAV releasing three smoke grenades consecutively, the model was expanded to eight decision variables. Considering the spatiotemporal synergistic effects of smoke clouds, the PSO algorithm maximized the combined shielding duration. The objective function rapidly decreased during the initial algorithm phase before stabilizing. Finally, for a scenario involving five drones each releasing up to three smoke grenades, the high-dimensional problem was decomposed into two stages. The PSO algorithm was employed to determine the maximum total effective screening duration. This model provides a scientific strategy for drone smoke interference. Its advantages include PSO's efficient handling of nonlinear non-convex problems, while the staged approach reduces dimensionality and avoids getting stuck in local optima.

Keywords: Particle swarm optimization algorithm, two-stage decomposition algorithm, shielding optimization model.

1. Introduction

This paper focuses on optimizing effective shielding strategies for drone smoke grenades, aiming to maximize shielding duration under various drone and smoke grenade configurations by integrating the Particle Swarm Optimization (PSO) algorithm [1]. First, for scenarios involving a single drone releasing a single smoke grenade, a model targeting shielding duration is constructed. Decision variables such as flight speed and heading angle are defined, and the PSO algorithm is employed to address the model's nonlinear and non-convex characteristics, yielding key optimization parameters [2]. Second, for scenarios involving a single drone consecutively releasing three smoke grenades, the decision variable dimension is expanded. A joint shielding model is established by leveraging the spatiotemporal synergistic effects of smoke clouds. Through iterative convergence using the PSO algorithm, optimal release and detonation parameters are obtained. Finally, for a high-dimensional scenario involving five drones each releasing up to three smoke grenades, a two-stage solution approach is adopted: first decomposing into individual drone subproblems to achieve local optimization, then performing global optimization using these as initial solutions while satisfying constraints such as speed and release intervals [3].

Experimental results demonstrate the PSO algorithm's excellent convergence, enabling efficient acquisition of optimal strategies that significantly enhance total effective shielding duration. This provides robust support for the engineering application of drone smoke interference.

2. Model establishment for single UAV and single smoke interference bomb shielding optimization

2.1. Model Establishment

The flight direction, flight speed, smoke interference bomb release point, and smoke interference bomb detonation point of FY1 are determined to maximize the shielding time. This objective is to maximize the shielding time, and the decision variables are defined as:

$$x = [v_{FY1}, \theta_{FY1}, t_{fly}, t_{fuse}]^T \quad (1)$$

The velocity vector of FY1 is a vector, which has both magnitude and direction distinction. Therefore, the velocity vector $\mathbf{v}_{FY1}(x)$ is jointly determined by the flight speed v_{FY1} and the flight heading angle θ_{FY1} :

$$\mathbf{v}_{FY1}(x) = \begin{bmatrix} v_{FY1} \cos \theta_{FY1} \\ v_{FY1} \sin \theta_{FY1} \\ 0 \end{bmatrix} \quad (2)$$

The detonation time $t_{det}(x)$ is the sum of the flight time and the fuse time:

Release Point Position:

$$P_{drop}(x) = P_{FY1}(0) + \mathbf{v}_{FY1}(x) \cdot t_{fly} \quad (3)$$

Displacement from Release to Detonation:

$$\Delta P = \mathbf{v}_{drop}(x) \cdot t_{fuse} + \frac{1}{2} \mathbf{g} \cdot t_{fuse}^2, \quad \text{where } \mathbf{v}_{FY1}(x) = \mathbf{v}_{drop}(x) \quad (4)$$

Therefore, the position of the detonation point is determined by the initial position of the UAV, the flight trajectory, and the projectile trajectory of the smoke bomb:

$$P_{det}(x) = P_{FY1}(0) + \mathbf{v}_{FY1}(x) \cdot t_{fly} + \mathbf{v}_{FY1}(x) \cdot t_{fuse} + \frac{1}{2} \mathbf{g} \cdot t_{fuse}^2 \quad (5)$$

For any time $t \geq t_{det}(x)$, the position of the smoke cloud center is:

$$P_{cloud}(t, x) = P_{det}(x) + \mathbf{v}_{cloud} \cdot (t - t_{det}(x)) \quad (6)$$

For any time t , given a set of x , the shielding judgment criterion is:

$$S(t, x) = \begin{cases} 1, & \text{if } \beta_{max}(t, x) \leq \alpha(t, x) \vee d(t, x) \leq R_{cloud} \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Half-Apex Angle of the Shielding Cone $\alpha(t, x)$:

$$\alpha(t, x) = \arcsin \left(\frac{R_{cloud}}{d(t, x)} \right), \quad \text{where } d(t, x) = \| P_{cloud}(t, x) - P_{M1}(t) \| \quad (8)$$

Maximum Line-of-Sight Deviation Angle $\beta_{max}(t, x)$:

$$\beta_{max}(t, x) = \max_{K_i \in K_T} \arccos \left(\frac{(P_{cloud}(t, x) - P_{M1}(t)) \cdot (K_i - P_{M1}(t))}{\| P_{cloud}(t, x) - P_{M1}(t) \| \| K_i - P_{M1}(t) \|} \right) \quad (9)$$

The objective is to maximize the total effective shielding duration, which is the integral of the shielding state function over the effective time window of the smoke:

$$T_{eff}(x) = \int_{t_{det}(x)}^{t_{det}(x) + T_{smoke}} S(t, x) dt \quad (10)$$

The constraints on the UAV's speed, heading angle, pre-release flight time, and fuse time are as follows:

$$\begin{aligned}
 70 &\leq v_{FY1} \leq 140 \\
 -\pi &\leq \theta_{FY1} \leq \pi \\
 0.1 &\leq t_{fy} \leq 50 \\
 0.1 &\leq t_{fuse} \leq 15
 \end{aligned} \tag{11}$$

2.2. Model Solution

The objective function of this optimization model is highly nonlinear, non-convex, and difficult to differentiate. Therefore, the Particle Swarm Optimization (PSO) algorithm [4] is selected for solving the model.

In the PSO algorithm, each particle represents a set of candidate solutions. Let the position and velocity of the i -th particle in the k -th generation be x_i^k and u_i^k respectively; the update rules are as follows:

$$\begin{aligned}
 u_i^{k+1} &= \omega u_i^k + c_1 r_1 (p_i^k - x_i^k) + c_2 r_2 (g^k - x_i^k) \\
 x_i^{k+1} &= x_i^k + u_i^{k+1}
 \end{aligned} \tag{12}$$

Among the parameters: x_i^{k+1} and u_i^{k+1} represent the position and velocity of the i -th particle in the $(k+1)$ -th generation respectively; ω denotes the inertia weight, which adjusts the continuity of velocity; c_1 and c_2 stand for the individual learning factor and social learning factor respectively; r_1 and r_2 represent independent random numbers, which are usually resampled for each dimension, each particle, and each generation; p_i^k is the individual historical optimal position of the i -th particle up to the k -th generation; and g^k is the global optimal position of the population in the k -th generation.

The iterative convergence curve of the PSO algorithm is plotted, and the specific results are shown in the Fig. 1

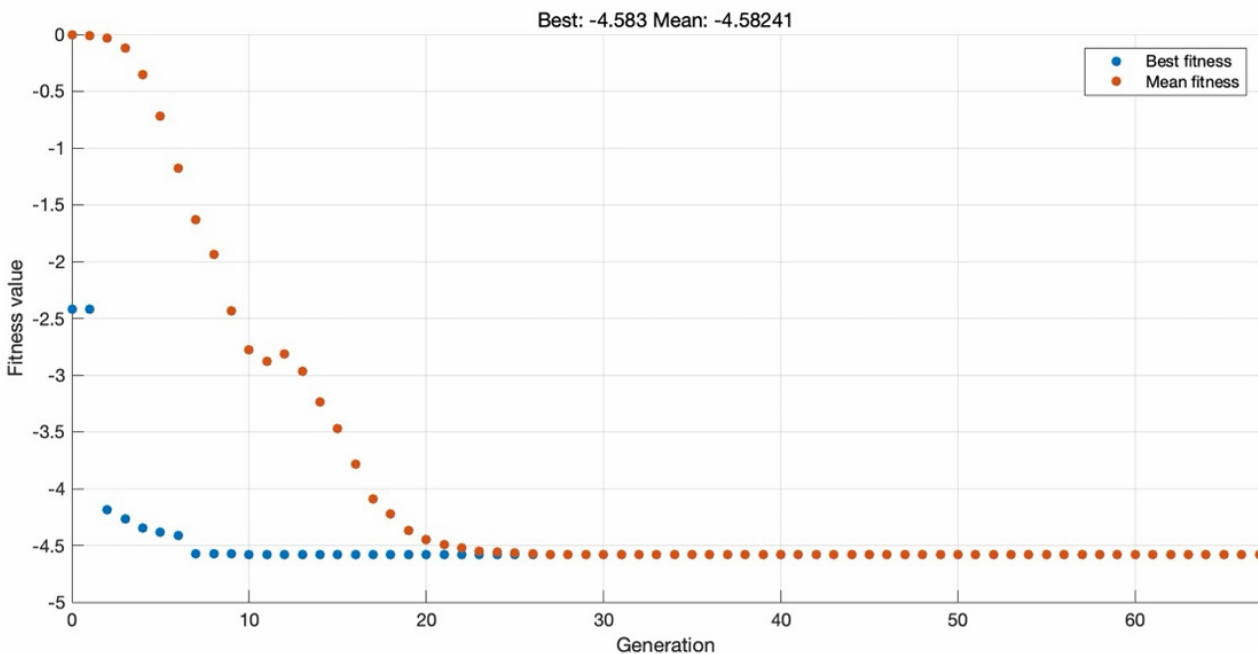


Fig. 1 Iterative convergence curve of the PSO algorithm

As can be seen from the Fig. 1, the Particle Swarm Optimization (PSO) algorithm exhibits excellent convergence. In particular, after 25 iterations, the value of the objective function remains basically unchanged, indicating that the algorithm has approached either the global optimal solution or a local optimal solution at this point. The specific optimized results are shown in the Fig. 2 below.

Optimal strategy simulation | Time: 8.00 s | Status: Not occluded | Cumulative occlusion time: 4.54 s

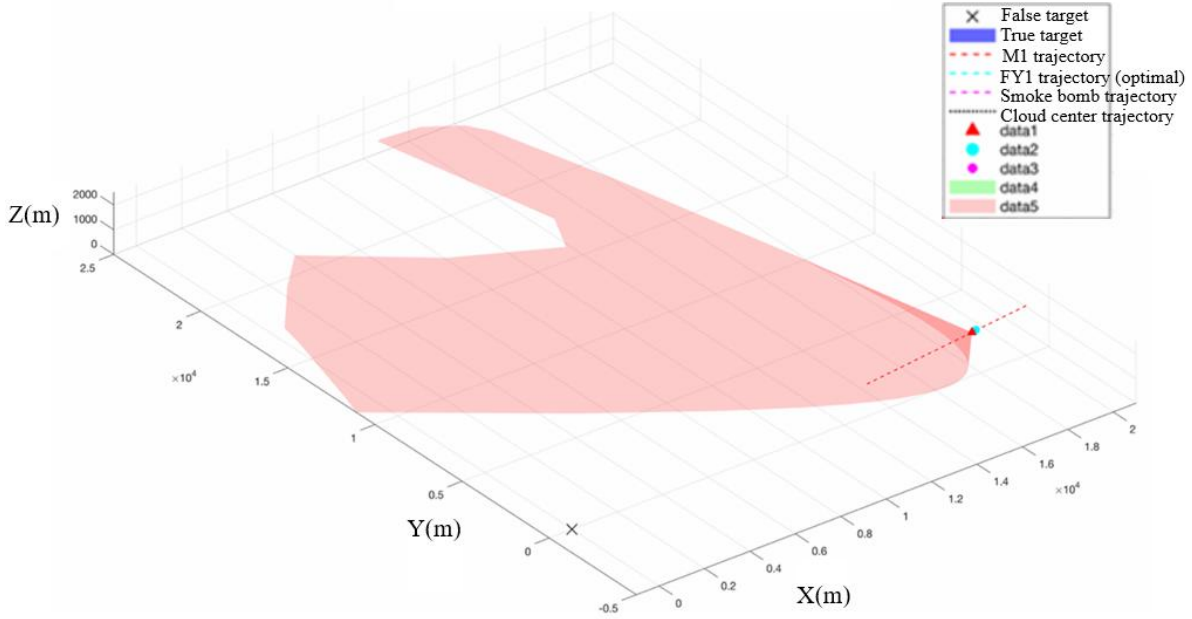


Fig. 2 Simulation results at 8s

When $t = 8s$, the shielding cone completely transforms into an irregular saddle shape, and thereafter, the shielding cone gradually dissipates. Thus, the final calculation results for are as follows:

UAV flight speed: 71.06m/s; UAV flight direction: 177.17° ; Pre-release flight time: 0.16s
Smoke bomb fuse time: 2.57s; Maximum effective shielding duration: 4.539s .

3. Model Establishment for Single UAV and Three Smoke Interference Bombs Joint Shielding Optimization

3.1. Model Establishment

A continuous release strategy involving three smoke bombs is designed for a single UAV to maximize the joint shielding duration of smoke clouds on the missile. The key lies in the synergistic effect of smoke clouds in both space and time—specifically, multiple smoke clouds can enhance the shielding effect through a relay or complementary approach.

The UAV adopts a fixed flight direction and speed determined in advance, while three smoke bombs are assigned respective release times and fuse times. Consequently, the decision variables are expanded to an 8-dimensional vector, defined as:

$$x = [\theta_{FY1}, v_{FY1}, t_{fly,1}, t_{fuse,1}, t_{fly,2}, t_{fuse,2}, t_{fly,3}, t_{fuse,3}]^T \quad (13)$$

The velocity vector of FY1 is a vector with both magnitude and direction. Thus, the velocity vector $\mathbf{v}_{FY1}(x)$ is jointly determined by the flight speed v_{FY1} and the flight heading angle θ_{FY1} :

$$\mathbf{r}_{v_{FY1}}(x) = \begin{bmatrix} v_{FY1} \cos \theta_{FY1} \\ v_{FY1} \sin \theta_{FY1} \\ 0 \end{bmatrix} \quad (14)$$

The detonation time $t_{det,j}(x)$ is the sum of the pre-release flight time and the fuse time.

Therefore, the position of the detonation point is determined by the initial position of the UAV, the UAV's flight trajectory, and the projectile trajectory of the smoke bomb:

$$P_{det,j}(x) = P_{FY1}(0) + \mathbf{r}_{v_{FY1}}(x) \cdot t_{fly,j} + \mathbf{r}_{v_{FY1}}(x) \cdot t_{fuse,j} + \frac{1}{2} \mathbf{r}_g \cdot t_{fuse,j}^2 \quad (15)$$

For any time $t \geq t_{det,j}(\mathbf{x})$, the position of the center of the j -th smoke cloud is:

$$P_{cloud,j}(t, x) = P_{det,j}(x) + v_{cloud} \cdot (t - t_{det,j}(x)) \tag{16}$$

Single Cloud Shielding: At time t , for a given strategy x , the set of key points shielded by the j -th smoke cloud, denoted as $J_j(t, x)$, is defined as:

$$J_j(t, x) = \{i \in \{1, \dots, 8\} \mid \text{Key point } K_i \text{ is shielded by Cloud } j\} \tag{17}$$

Among the above, the criterion for determining whether key point K_i is shielded by Cloud j is as follows: when viewed from the missile at position $P_{M1}(t)$, point K_i lies within the shielding cone formed by Cloud j , or the missile itself is inside Cloud j .

Joint Shielding: At time t , the joint shielding state function $S_{joint}(t, x)$ is defined as:

$$S_{joint}(t, x) = \begin{cases} 1, & \text{if } \bigcup_{j=1}^3 J_j(t, x) = K_T \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

The objective is to maximize the total effective shielding duration, which is the integral of the joint shielding state function over the effective time window of the smoke:

$$T_{eff}(x) = \int_0^{T_{end}} S_{joint}(t, x) dt \tag{19}$$

3.2. Model Solution

The Particle Swarm Optimization (PSO) algorithm is used to solve this planning problem, and the iterative convergence curve of the PSO algorithm is obtained. The PSO algorithm exhibits excellent convergence. In the initial stage, the value of the objective function decreases rapidly; as the number of iterations increases, the curve tends to flatten, and finally the objective function value remains basically unchanged. This indicates that the algorithm has approached either the global optimal solution or a local optimal solution at this point. The optimized results are shown in the Fig. 3.

Optimal strategy simulation | Time: 7.00 s | Status: Effective occlusion | Cumulative occlusion time: 6.00 s

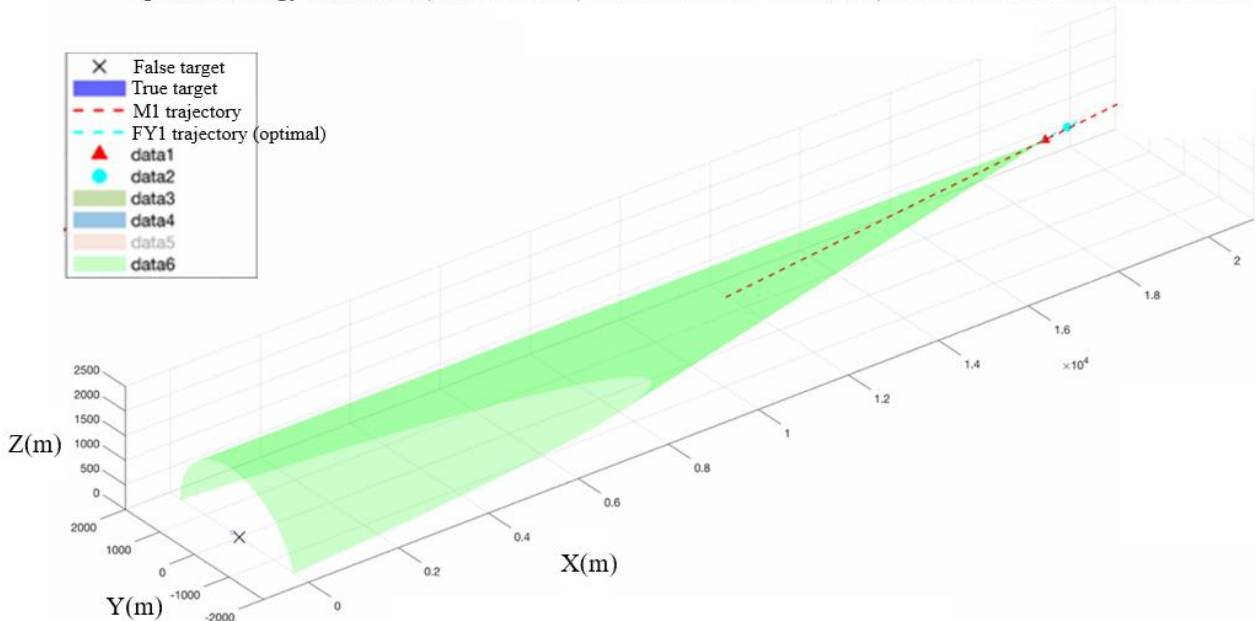


Fig. 3 Simulation results at 7s

At $t = 7s$, the cumulative shielding duration has reached 6s, and there will still be an additional 0.34s of effective shielding time afterward. Therefore, the optimized results are as follows:

Flight direction: 8.840° ; Flight speed: 98.53m/s ; Total effective shielding duration: 6.34s .
Specific details of the three smoke bombs are shown in the Table 1:

Table 1. Three Scheme comparing

Smoke Bomb	Pre-release flight time	Smoke bomb fuse time	Independent contribution to effective duration
1st	0.000s	0.016s	2.620s
2nd	1.064s	0.002s	3.890s
3rd	9.954s	0.145s	0.000s

4. Model Establishment for Multi-UAV and Multi-Smoke Interference Bombs Cooperative Shielding Optimization

4.1. Model Establishment

Considering 5 UAVs simultaneously, with each UAV capable of releasing up to 3 smoke interference bombs, Due to the excessively high dimensionality, it is decomposed into 2 stages.

Stage 1: The high-dimensional, strongly coupled multi-UAV problem is decomposed into 5 mutually independent low-dimensional subproblems. For each UAV, an individual optimal control parameter solution is constructed with the objective of "maximizing the shielding contribution to the three missiles" [5].

Stage 2: Using the 5 sets of prior parameters obtained from Stage 1 as initial solutions, global optimization is performed. This balances exploration and exploitation while avoiding trapping in local optima [6].

The criteria are divided into two scenarios: judgment of a single smoke cloud on a single missile, and joint judgment of multiple smoke clouds on a single missile.

Scenario 1: Judgment of a Single Smoke Cloud

For a missile M_m at position $\overset{\cdot}{P}_{M,m}(t)$ at time t , and a smoke cloud $B_{k,j}$ at position $\overset{\cdot}{P}_{cloud,k,j}(t, \mathbf{x})$ at the same time, this model determines which points in K_T can be shielded by the cloud. The specific model is constructed as follows:

Calculation of Distance Between Missile and Smoke Cloud Center:

$$d = \|\overset{\cdot}{P}_{cloud,k,j} - \overset{\cdot}{P}_{M,m}\| \quad (20)$$

If $d \leq R_{cloud}$, all key points are shielded.

If $d > R_{cloud}$, calculate the half-apex angle α of the shielding cone:

$$\alpha = \arcsin\left(\frac{R_{cloud}}{d}\right) \quad (21)$$

For each key point $\overset{\cdot}{K}_i \in K_T$, calculate the deviation angle β_i between $\overset{\cdot}{K}_i$ and the axis of the shielding cone. The axis of the shielding cone is:

$$\overset{\cdot}{V}_{axis} = \overset{\cdot}{P}_{cloud,k,j} - \overset{\cdot}{P}_{M,m} \quad (22)$$

The deviation angle β_i is then:

$$\beta_i = \arccos\left(\frac{\overset{\cdot}{V}_{axis} \cdot (\overset{\cdot}{K}_i - \overset{\cdot}{P}_{M,m})}{\|\overset{\cdot}{V}_{axis}\| \|\overset{\cdot}{K}_i - \overset{\cdot}{P}_{M,m}\|}\right) \quad (23)$$

If $\beta_i \leq \alpha$, the point $\overset{\cdot}{K}_i$ is shielded.

Scenario 2: Joint Judgment of Multiple Smoke Clouds on a Single Missile

The shielding judgment for missile m at time t is considered effective if all key points of the real target are shielded by any one or more of the 15 smoke bombs relative to missile m .

Objective Function and Decision Variables

Under the above judgment criteria, the objective function is to maximize the effective shielding time of the smoke bombs on the three missiles:

$$\max T_{total}(x) = \sum_{m=1}^3 \int_{T_{start}}^{T_{end}} S_m(t, x) dt \tag{24}$$

The decision variables form a 40-dimensional vector:

$$x = [x_1^T, x_2^T, x_3^T, x_4^T, x_5^T]^T, \text{ where } x_1 = [\theta_{FY1}, v_{FY1}, t_{fly,1,1}, t_{fuse,1,1}, t_{fly,1,2}, t_{fuse,1,2}, t_{fly,1,3}, t_{fuse,1,3}]^T \tag{25}$$

Constraints: For each UAV $k \in \{1, \dots, 5\}$, the constraints are as follows:

1. Speed Constraint: $70 \leq v_{FY,k} \leq 140$;
2. Pre-release Flight Time Constraint: $0 \leq t_{fly,k,j} \leq 50$;
3. Fuse Time Constraint: $0 \leq t_{fuse,k,j} \leq 2 \cdot \frac{z_{FY,k}(0)}{g}$;
4. Heading Angle Constraint: $\theta_{FY,k} \in [\theta_{min,k}, \theta_{max,k}]$.
5. For the same UAV, the release times: $t_{fly,k,2} - t_{fly,k,1} \geq 1, t_{fly,k,3} - t_{fly,k,2} \geq 1$.

4.2. Model Solution

Similarly, this paper uses the Particle Swarm Optimization algorithm to solve the planning problem, and the maximum total effective shielding duration is 21.7s. The specific strategies are as follows, and the deployment details of one of the drones are shown in Table 2:

Optimal cooperative strategy for UAV FY1: Flight direction: 8.481° , Flight speed: 89.584m/s.

Optimal cooperative strategy for UAV FY2: Flight direction: 230.655° , Flight speed: 89.827m/s.

Optimal cooperative strategy for UAV FY3: Flight direction: 85.440° , Flight speed: 98.845m/s.

Optimal cooperative strategy for UAV FY4: Flight direction: 247.310° , Flight speed: 92.327m/s.

Optimal cooperative strategy for UAV FY5: Flight direction: 15.699° , Flight speed: 85.917m/s.

Table 2. Details for UAV FY2

Smoke Bomb	Pre-release flight time	Smoke bomb fuse time	Obstructing the target	Independent contribution to effective duration
1st	5.997s	4.371s	/	0.00s
2nd	9.618s	5.371s	M2	3.25s
3rd	12.379s	7.647s	M1	3.35s

5. Conclusion

This paper proposes an optimization model for shielding drone smoke decoy flares and a particle swarm optimization (PSO) algorithm solution framework. The model's core advantages lie in its multi-scenario adaptability and efficient computation—it dynamically builds models based on drone and flare configurations, while PSO overcomes bottlenecks in nonlinear non-convex problems. Its purpose is to provide decision support for jamming missions and reduce trial-and-error costs in actual

deployments. First, in a single-UAV, single-smoke-grenade scenario, the model defines key variables, converging in just 25 PSO iterations to deliver a baseline jamming solution. Second, for a single-UAV, triple-grenade scenario, the model expands to 8-dimensional variables. The second grenade is pre-released at 1.064 seconds, independently contributing 3.890 seconds to achieve relay jamming, with PSO rapidly optimizing the combined jamming duration. Then, in a five-drone scenario, the model decomposed the 40-dimensional problem into two phases. For instance, FY2's second missile contributed 3.25s to M2, preventing the algorithm from getting stuck in local optima. Finally, the model covered multiple scenarios with quantitative constraints, balancing theory and practicality to provide reference for engineering deployment. Future research could further integrate dynamic environmental parameters to optimize algorithm response capabilities.

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