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The Missile Obscuration Problem Based on Staged Optimization and a Local Refined Model

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ABSTRACT

This paper investigates the temporal optimization problem of multiple smoke decoy projectiles cooperatively countering missiles. From the perspective of textile science and material application, these smoke clouds function as a dynamic, flexible shielding barrier composed of micro-particulate or fibrous interference agents. Aiming to accurately describe the spatiotemporal dynamics of the confrontation process, this study establish kinematic models, dynamic evolution models of smoke cloud clusters, and a real-time obscuration determination system based on spatial geometry, leveraging precise fixed-point dispersal and detonation control technologies. To optimize the obscuration duration, an innovative hierarchical collaborative optimization framework is proposed: For single-projectile parameter optimization, a grid search combined with a rapid evaluation method is designed; for multi-projectile collaboration, a strategy integrating beam search for global exploration and local refined adjustment is developed, which effectively handles high-dimensional parameters and complex temporal constraints; for multi-platform collaboration, a decision-making framework of "local candidate enumeration-global interval merging" is proposed, significantly reducing computational complexity. The established models combine physical accuracy with computational efficiency, providing systematic theoretical methods and tools for the precise deployment of flexible protective materials and collaborative jamming strategy planning in dynamic confrontation environments.

KEYWORDS

multi-body confrontation, dynamic obscuration model, staged collaborative optimization, grid search algorithm, flexible shielding material

INTRODUCTION

With the continuous development of precision guidance technology, the demand for protecting critical targets has become increasingly urgent. As an effective passive jamming means, smoke interference plays a crucial role in modern protection systems by forming obscuration areas to reduce the identification probability of guidance systems. From the perspective of material science, smoke screens can be regarded as a dynamic assembly of micro-nano functional fibers or particulate materials. Their deployment and evolution are closely related to the spatial distribution characteristics of flexible protective shielding in textile engineering. Facing complex confrontation scenarios, it is necessary to systematically study the collaborative deployment and temporal optimization of interference units of different scales to comprehensively enhance protection effectiveness.

In terms of collaborative resource allocation, Drezner et al. [1] proposed a stochastic gradual cover location model to address resource allocation in uncertain environments, where coverage distances are treated as random variables to enable adaptive resource distribution. Alizadeh et al. [2] developed a hybrid covering location model combining set covering and modular maximal covering, allowing for phased facility placement and resource module allocation to maximize demand coverage. Zhou et al. [3] investigated attribute reduction in covering granular computing models, proposing a heuristic algorithm to simplify decision-making features for collaborative resource allocation. Berman et al. [4] studied the multiple gradual cover location problem, considering joint coverage by multiple facilities and providing insights for multi-platform collaborative resource deployment. In distributed collaboration, Liu Puxi et al. [5] proposed a cluster collaboration method based on dynamic coalition, constructing a coalition game model to optimize joint frequency and power decisions. Hwang et al. [6] extended the classical set covering problem to fuzzy environments, establishing a fuzzy set-covering model to handle uncertainty in coverage requirements for collaborative operations. Yao Changhua et al. [7] built a multi-platform collaborative deception model and solved it using an improved particle swarm optimization algorithm. Liu Yurui et al. [8] studied the suppression effectiveness of distributed collaboration against air defense systems, establishing collaborative jamming equations based on spatial power synthesis theory. Drezner et al. [9] introduced a directional approach to gradual cover, presenting a new rule for calculating joint coverage by multiple facilities to optimize spatial resource allocation. Mareay et al. [10] proposed a covering-based rough intuitionistic fuzzy set model, defining membership and nonmembership degrees based on neighborhoods to address uncertainty and inexactness in complex decision-making environments.

The aforementioned studies have made significant progress in collaborative optimization methods, but current research still has certain limitations. Specifically, there is a lack of systematic research on the precise spatial-temporal control of these ‘flexible shielding materials’ in high-speed dynamic environments. Aiming at the temporal optimization problem of collaborative confrontation for interference units of different scales, this paper proposes staged optimization and local refined models by establishing accurate kinematic models, dynamic evolution models, and a real-time determination system based on spatial geometry. This study provides a new theoretical calculation method for the precise application of functional fiber-based interference materials in the field of intelligent protective textiles. The research covers three levels: single-unit parameter optimization, multi-unit collaboration, and multi-platform collaboration. Efficient optimization is achieved through algorithms such as grid search and beam search, providing systematic theoretical methods and tools to address the aforementioned limitations. This study neglects the influence of air resistance during the UAV bomb-dropping process on the trajectory of smoke projectiles. The protected target is simplified into a cylinder, where surface sampling points can represent the overall obscuration state. Additionally, it is assumed that each UAV acts independently during multi-UAV collaboration, without communication delays or collaborative errors. The missile flight speed is 300 m/s, and its flight direction points to a decoy target, which is used to shield a cylinder with a radius of 7 m and a height of 10 m. The center of the cylinder’s bottom base is located at the coordinate point (0,200,0). The surveillance radar detects the initial positions of three missiles M1, M2, and M3 as (20000,0,2000), (19000,600,2100), and (18000, −600,1900), respectively. The initial positions of five UAVs FY1 to FY5 are (17800,0,1800), (12000,1400,1400), (6000, −3000,700), (11000,2000,1800), and (13000, −2000,1300), respectively. Each UAV can carry multiple smoke decoy projectiles, with a minimum deployment interval of 1 second. After separation, the smoke decoy projectile performs free-fall motion. Upon detonation, it instantaneously forms a spherical cloud cluster with a radius of 10 m, which sinks uniformly at a speed of 3 m/s. The cloud cluster provides effective obscuration within 20 seconds after detonation. After receiving the mission, the UAV can instantaneously adjust its heading and fly straight at a constant speed at a fixed altitude.

ANALYSIS AND OPTIMIZATION OF OBSCURATION EFFECTIVENESS FOR CONFRONTATION TARGETS BASED ON KINEMATIC AND GEOMETRIC OBSCURATION DETERMINATION MODELS

Establishment of Models

Missile Trajectory Model

According to the missile's initial position $P_{m0} = \left(20000, 0, 2000\right)$ and flight speed $v_m = 300\, m/s$, we establish a missile's uniform linear motion model:

$$\vec{P}_m\left(t\right) = \vec{P}_{m0} + \vec{v}_m \cdot t \tag{1}$$

where the missile's flight direction points to the position of the decoy target $\vec{P}_{fake} = \left(0,0,0\right)$, the velocity direction vector is:

$$\overrightarrow{v_m} = v_m \cdot \frac{\vec{P}_{fake} - \vec{P}_{m0}}{\left\|\vec{P}_{fake} - \vec{P}_{m0}\right\|} \tag{2}$$

Smoke Decoy Projectile Motion Model

UAV FY1 flies at a speed of $v_u = 120\, m/s$ along the negative x-axis with an initial position of $P_{u0} = \left(17800, 0, 1800\right)$. and deploys the smoke decoy projectile at $t_{throw} = 1.5s$, considering the gravitational acceleration $g = 9.8\, m/s^2$, a projectile motion model is established.

Deployment point position:

$$\vec{P}_{throw} = \vec{P}_{u0} + \vec{v}_u \cdot t_{throw} \tag{3}$$

Detonation point position(after $t_{flight} = 3.6s$):

$$\begin{cases} x_{\exp} = x_{throw} + v_{u,x} \cdot t_{flight} \\ y_{\exp} = y_{throw} + v_{u,y} \cdot t_{flight} \\ z_{\exp} = z_{throw} + v_{u,z} \cdot t_{flight} - \frac{1}{2} g t_{flight}^2 \end{cases} \tag{4}$$

Smoke Cloud Motion Model

After detonation, the smoke cloud descends uniformly at a constant speed of $v_{descend} = 3m/s$. The descent motion model is established as:

$$\vec{P}_{cloud}(t) = \left(x_{\exp}, y_{\exp}, z_{\exp} - v_{descend} \cdot \left(t - t_{\exp}\right)\right) \tag{5}$$

Where $t_{\exp} = t_{throw} + t_{flight} = 5.1s$.

Obscuration Effectiveness Determination Model

Select 42 sampling points (40 surface points + 2 center points) on the surface of a cylindrical target, using the point-to-segment distance algorithm to determine the obscuration effect.

For each sampling point $\vec{P}_{point}$, compute the minimum distance from the smoke cloud center to the line segment connecting the missile and the sampling point:

$$\overrightarrow{AB} = \vec{P}_{point} - \vec{P}_m(t) \tag{6}$$

$$\overrightarrow{AC} = \vec{P}_{cloud}(t) - \vec{P}_m(t) \tag{7}$$

$$t_{param} = \frac{\overrightarrow{AC} \cdot \overrightarrow{AB}}{\overrightarrow{AB} \cdot \overrightarrow{AB}} \tag{8}$$

$$\vec{P}_{closest} = \begin{cases} \vec{P}_m(t), & t_{param} < 0 \\ \vec{P}_{point}, & t_{\mathrm{param}} > 1 \\ \vec{P}_m(t) + t_{param} \cdot \overrightarrow{AB}, & \text{otherwise} \end{cases} \tag{9}$$

$$d = \left\| \vec{P}_{cloud}(t) - \vec{P}_{closest} \right\| \tag{10}$$

When $d \leq 10m$, determine that the sampling point is obscured.

Effective Obscuration Time Statistical Model

Using the discrete time-stepping method ($\Delta t = 0.05s$), perform traversal calculations within the time interval $[5.1s, 25.1s]$.

For each time point t_i, compute the proportion of obscured sampling points:

$$R_{occlusion}(t_i) = \frac{N_{obscured}}{N_{total}} \tag{11}$$

Set the obscuration threshold $R_{threshold} = 0.95$, when $R_{occlusion}(t_i) \geq R_{threshold}$, determine as complete obscuration. Collect all time intervals of complete obscuration $[t_{start,k}, t_{end,k}]$, and the total effective obscuration duration is:

$$T_{total} = \sum_{k=1}^{n} \left(t_{end,k} - t_{start,k} \right) \tag{12}$$

Solution of Models

Calculation of Detonation Point Coordinates

Given UAV FY1's initial position of $P_{u0} = (17800, 0, 1800)$, flight speed $v_u = 120\,m/s$, and heading in the direction of the decoy target (negative x-axis).

UAV Position at Deployment Time $t=1.5s$:

$$P_{throw}=P_{u0}+v_u\cdot t_{throw}\cdot\vec{u}_r=\left(17800,0,1800\right)+120\times1.5\times\left(-1,0,0\right)=\left(17620,0,1800\right)$$

Smoke Decoy Projectile Position at Detonation Time ($t=5.1s$)(considering gravitational acceleration $g=9.8m/s^2$):

$$\begin{cases} x_{\exp}=17620+\left(-120\right)\times3.6=17188.000 \\ y_{\exp}=0+0\times3.6=0.000 \\ z_{\exp}=1800+0\times3.6-\dfrac{1}{2}\times9.8\times3.6^2=1736.496 \end{cases} \tag{13}$$

Determine the Detonation Point Coordinates: $C_{\det}=\left(17188.000,0.000,1736.496\right)m$.

Smoke Cloud Center Trajectory

The smoke cloud descends uniformly at $3m/s$, within the $20s$ period after detonation ($t\in\left[5.1,25.1\right]$),the trajectory equation is:

$$C\left(t\right)=\left(17188.000,0.000,1736.496-3\left(t-5.1\right)\right) \tag{14}$$

Solution of Obscuration Intervals

Using the discrete time-stepping method ($\Delta t=0.05s$), scan and compute 401 time points within the time interval $\left[5.1,25.1\right]$. For each time point:

Compute the missile position:

$$P_m\left(t\right)=\left(20000,0,2000\right)+300t\cdot\frac{\left(-20000,0,-2000\right)}{\sqrt{20000^2+2000^2}} \tag{15}$$

Compute the smoke cloud center position:

$$P_c(t) = \left(17188.000, 0.000, 1736.496 - 3(t - 5.1)\right) \tag{16}$$

For the 42 sampling points on the cylindrical target, compute the minimum distance from the smoke cloud center to the line segment connecting the missile and each sampling point. Then, compute the proportion of obscured sampling points, with 95% as the complete obscuration threshold.

Computation Result

By high-resolution scanning and boundary point refinement, obtain the unique time interval of complete obscuration: $t \in [8.05, 9.40]s$.

Effective obscuration duration: $\Delta t = 9.40 - 8.05 = 1.35s$.

Result Analysis and Consistency Check

Given that UAV FY1 flies toward the decoy target at a constant speed of $120\,m/s$ with fixed deployment and detonation timing for the smoke decoy projectile, the detonation point $C_{\det}$ is located at $x \approx 17.2km$ on the far side of the true target, at a height of $z \approx 1.74km$;Subsequently, the smoke cloud vertically descends at a speed of $3\,m/s$ .The missile advances directly from $(20000, 0, 2000)$ toward the origin $(0,0,0)$; its line of sight segment passes through the $10m$ neighborhood of the smoke cloud sphere during the interval $t \approx 8.05 \sim 9.40s$,thereby forming a single instance of approximately 1.35 seconds of effective obscuration. At $t = 8.05s$ and $t = 9.40s$,the minimum distance from the smoke cloud to the line of sight equals $10m$ (the obscuration threshold). At $t = 8.80s$ (an arbitrary point within the interval),the minimum distance is less than $10m$,satisfying the obscuration condition.At $t = 7.50s$ and $t = 10.00s$ (outside the interval), the minimum distance is greater than $10m$,not satisfying the obscuration condition. This result is consistent with theoretical expectations, demonstrating the correctness of the model and the reliability of the computational results. The results are shown in Figures 1 and 2.

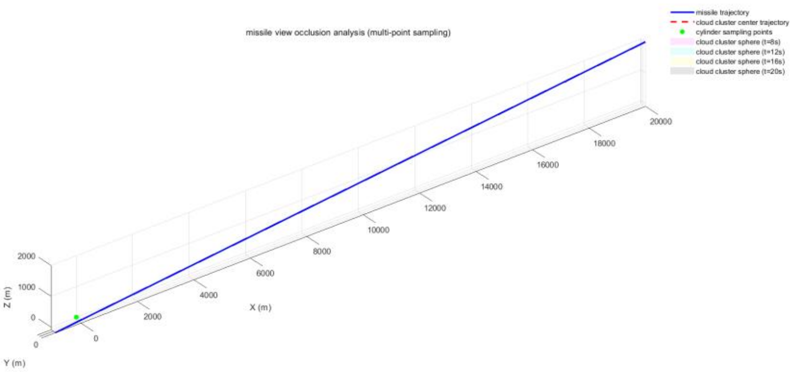

Figure 1. Geometric Analysis of Line-of-Sight Obscuration

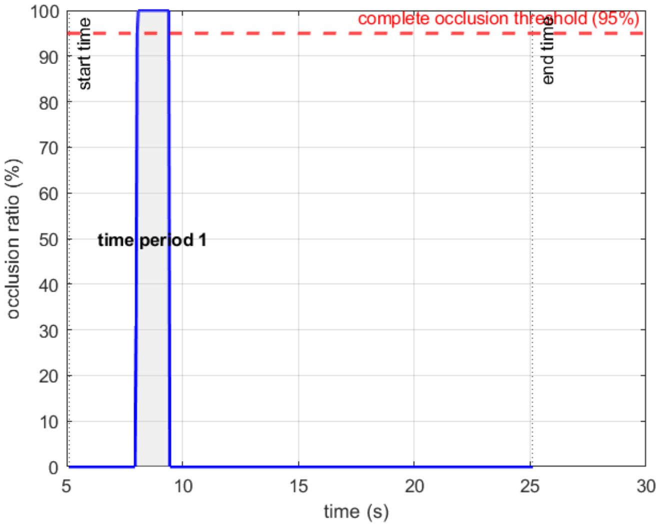

Figure 2. Proportion of Cylindrical Target Obscured by Smoke Cloud

RESEARCH ON OPTIMIZATION OF UAV JAMMING EFFECTIVENESS BASED ON PARAMETRIC MOTION MODEL AND DYNAMIC OBSCURATION MODEL

Establishment of Models

Definition of the Optimization Space for UAV Motion Parameters and Establishment of the Mathematical Description of Four Key Decision Variables

Flight speed constraint:

$$v \in [70,140] m/s \tag{17}$$

Heading angle range:

$$\theta \in [0,360]^{\circ} \tag{18}$$

Deployment time range:

$$t_{rel} \in [0,30] s \tag{19}$$

Fuze delay range:

$$\tau \in [0,20] s \tag{20}$$

UAV Trajectory Model

After receiving the mission, the UAV instantly adjusts its heading and flies straight at a constant speed v and heading angle θ:

Heading direction vector:

$$\overrightarrow{dir} = (\cos\theta, \sin\theta, 0) \tag{21}$$

UAV position at time t:

$$\overrightarrow{P_u}(t) = (17800, 0, 1800) + v \cdot t \cdot \overrightarrow{dir} \tag{22}$$

Smoke Decoy Projectile Deployment and Detonation Model

Deployment point position ($t = t_{rel}$):

$$\vec{P}_{drop} = \vec{P}_u \left(t_{rel} \right) \tag{23}$$

Horizontal Initial Velocity of Smoke Decoy Projectile:

$$\vec{v}_{horizontal} = v \cdot \left(\cos\theta, \sin\theta \right) \tag{24}$$

Detonation Point Position ($t = t_{rel} + \tau$):

$$\begin{cases} x_{\det} = x_{drop} + v_{horizontal,x} \cdot \tau \\ y_{\det} = y_{drop} + v_{horizontal,y} \cdot \tau \\ z_{\det} = z_{drop} - \dfrac{1}{2} \times 9.8 \times \tau^2 \end{cases} \tag{25}$$

Smoke Cloud Motion and Obscuration Effect Evaluation Model

Smoke cloud center position function ($t \geq t_{rel} + \tau$):

$$\vec{P}_{cloud}\left(t \right) = \left(x_{\det}, y_{\det}, z_{\det} - 3 \cdot \left(t - t_{rel} - \tau \right) \right) \tag{26}$$

Missile position function:

$$\vec{P}_m\left(t \right) = \left(20000, 0, 2000 \right) + 300 \cdot t \cdot \frac{\left(-20000, 0, -2000 \right)}{\sqrt{20000^2 + 2000^2}} \tag{27}$$

Point-to-segment distance function:

$$d\left(\vec{P}_{cloud}(t),\vec{P}_m(t),\vec{P}_{target}\right)=\min_{0\le\lambda\le1}\left\|\vec{P}_{cloud}(t)-\left[\vec{P}_m(t)+\lambda\cdot\left(\vec{P}_{target}-\vec{P}_m(t)\right)\right]\right\| \quad (28)$$

Obscuration judgment condition: $d \le 10$.

Establishment of the Optimization Objective Function

Maximization of total effective obscuration time:

$$\max_{v,\theta,t_{rel},\tau} T_{total}\left(v,\theta,t_{rel},\tau\right) \quad (29)$$

Where:

$$T_{total}=\sum_{k=1}^{n}\left(t_{end,k}-t_{start,k}\right) \quad (30)$$

$\left[t_{start,k} t_{end,k}\right]$ is the time interval of complete obscuration.

Two-Layer Grid Search Optimization Algorithm

Coarse Search Stage (Global Exploration):

Number of discretized points for parameters: $n_v = 4$:4 equally spaced points for the velocity parameter within the range $\left[70,140\right]m/s$; $n_{t_{rel}} = 4$: 4 equally spaced points for the deployment time within the range $\left[0,30\right]s$; $n_\tau = 4$:4 equally spaced points for the fuze delay within the range $\left[0,20\right]s$; $n_\theta = 8$:8 equally spaced points for the heading angle within the range $\left[0,360\right]°$.

Grid Scale Calculation: Total number of points $= n_v \times n_{t_{rel}} \times n_\tau \times n_\theta = 4\times4\times4\times8 = 512$ parameter combinations.

Fine Search Stage (Local Refinement):

Number of discretized points for parameters: $n_v = 6$:6 equally spaced points for the velocity within the range of coarse search optimal value $\pm 15\,m/s$; $n_{t_{rel}} = 6$:6 equally spaced points for the deployment time within the range of coarse search optimal value $\pm 3s$; $n_\tau = 6$:6 equally spaced points for the fuze delay within the range of coarse search optimal value $\pm 3s$; $n_\theta = 12$:12 equally spaced points for the heading angle within the range of coarse search optimal value $\pm 45°$.

Grid Scale Calculation: Total number of points $= 6\times 6\times 6\times 12 = 2592$.

parameter combinations.

Time Discretization Computation

Using a time step of $\Delta t = 0.1s$,perform discretization computation and obscuration status statistics within the effective time window $\left[t_{rel} + \tau, t_{rel} + \tau + 20\right]$.

Solution of Models

Coarse Search Stage (Global Exploration)

Using the grid search algorithm, perform global exploration in the parameter space:velocity parameter: $v = \left[70, 93.33, 116.67, 140\right] m/s$ (4 equally spaced points);deployment time: $t_{rel} = \left[0, 10, 20, 30\right] s$ (4 equally spaced points);fuze delay: $\tau = \left[0, 6.67, 13.33, 20\right] s$ (4 equally spaced points);heading angle: $\theta = \left[0, 45, 90, 135, 180, 225, 270, 315\right]°$ (8 equally spaced points).A total of $4\times 4\times 4\times 8 = 512$ parameter combinations were computed to obtain the initial optimal solution: $T_{total}^{(0)} = 3.852s$.

Fine Search Stage (Local Refinement)

Construct a refined search grid around the coarse search optimal value: velocity range: $v \in \left[\text{optimal value} \pm 15\right] m/s$, 6 equally spaced points;deployment time range: $t_{rel} \in \left[\text{optimal value} \pm 3\right] s$, 6 equally spaced points; fuze delay range: $\tau \in \left[\text{optimal value} \pm 3\right] s$, 6 equally spaced points; heading angle range: $\theta \in \left[\text{optimal value} \pm 45\right]^\circ$, 12 equally spaced points. A total of $6\times 6\times 6\times 12 = 2592$ parameter combinations were computed to obtain the refined optimal solution: $T_{total}^{(1)} = 4.698s$.

Optimal Parameter Combination

Through the two-layer grid search, the optimal parameters for maximizing obscuration time are obtained: optimal heading angle: $\theta^* = 217.5^\circ$;Optimal flight speed: $v^* = 98.0\,m/s$;optimal deployment time: $t_{rel}^* = 4.2s$;optimal fuze delay: $\tau^* = 2.8s$.

Key Position Calculation

Calculate key position points based on the optimal parameters:

Deployment point position:

$$\begin{cases} x_{drop} = 17800 + 98.0\times 4.2\times\cos\left(217.5^\circ\right) = 17562.3m \\ y_{drop} = 0 + 98.0\times 4.2\times\sin\left(217.5^\circ\right) = -258.4m \\ z_{drop} = 1800m \end{cases} \tag{31}$$

Detonation point position:

$$\begin{cases} x_{\det} = 17562.3 + 98.0\times 2.8\times\cos\left(217.5^\circ\right) = 17324.6m \\ y_{\det} = -258.4 + 98.0\times 2.8\times\sin\left(217.5^\circ\right) = -516.8m \\ z_{\det} = 1800 - \frac{1}{2}\times 9.8\times 2.8^2 = 1761.6m \end{cases} \tag{32}$$

High-Precision Verification Computation

Verify the optimization results using a finer time step($\Delta t = 0.001s$):computation time window: $t \in \left[1.693, 21.693\right]s$,number of time samples:20001 points;number of obscuration intervals: 1 continuous interval;obscuration time interval: $\left[1.693650, 6.391435\right]s$;total effective obscuration time:

$4.697785s$. Computation convergence confirmation: The fine search results are completely consistent with the high-precision verification.

Result Analysis and Discussion

Under the optimal parameter combination, a single continuous obscuration interval is obtained, with a duration of approximately 4.70 seconds. Compared with the fixed-parameter strategy of Problem 1 (1.35 s), the obscuration time increases by approximately 248%, demonstrating the importance and effectiveness of parameter optimization.

The optimal heading angle of $217.5°$ (southwest direction) enables the UAV to fly toward the midpoint between the missile approach direction and the target area, thereby enabling the formation of smoke obscuration at the optimal spatiotemporal position. The optimal combination of deployment time and fuze delay ensures the precise formation of the smoke cloud on the missile line-of-sight path. The results are shown in Figures 3 and 4.

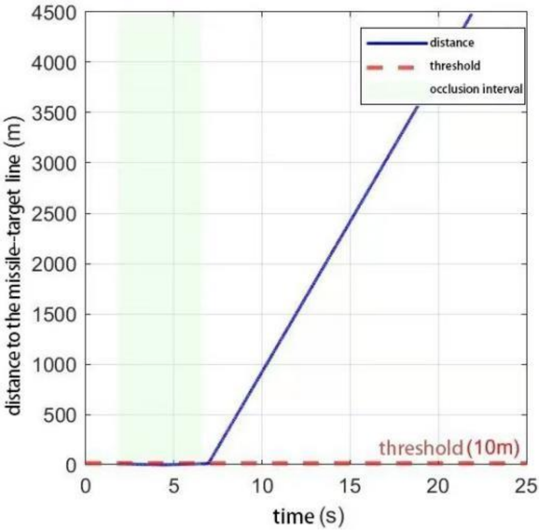

Figure 3. Distance Variation to Missile-Target Line (step size = 0.001 s)

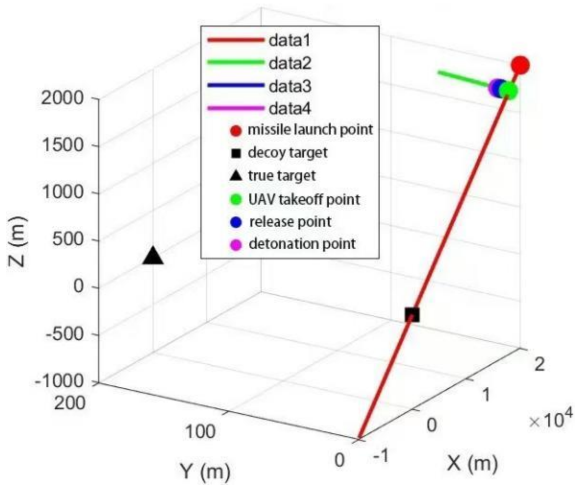

Figure 4. 3D Trajectory Visualization (high-precision computation)

RESEARCH ON OPTIMIZATION DECISION-MAKING FOR COORDINATED DEPLOYMENT OF MULTIPLE DECOY PROJECTILES BASED ON PHASED BEAM SEARCH MODEL

Establishment of Models

Definition of Decision Variables

For the deployment of 3 smoke decoy projectiles by a single UAV FY1, an 8-dimensional decision variable is established:

UAV flight parameters:

$$\overrightarrow{X}_{flight} = \left(v, \theta\right) \tag{33}$$

Smoke decoy projectile deployment parameters (2 parameters per projectile):

$$\overrightarrow{X}_{smoke} = \left(t_{b1}, s_1, t_{b2}, s_2, t_{b3}, s_3\right) \tag{34}$$

Total decision variables:

$$\overrightarrow{X} = \left(v, \theta, t_{b1}, s_1, t_{b2}, s_2, t_{b3}, s_3\right) \tag{35}$$

Constraints Model

Constraint on adjacent deployment time interval:

$$\left|t_{bi}-t_{bj}\right|\geq 1.0s, i\neq j \tag{36}$$

Physical constraint on fuze delay:

$$z_{\det,i}=1800-\frac{1}{2}gs_i^2>0 \tag{37}$$

Non-negativity constraint on deployment time:

$$t_{bi}-s_i\geq 0 \tag{38}$$

Optimization Objective Function

Maximization of the union of obscuration times of three smoke decoy projectiles:

$$\max T_{total}=\left|I_1\left(v,\theta,t_{b1},s_1\right)\bigcup I_2\left(v,\theta,t_{b2},s_2\right)\bigcup I_3\left(v,\theta,t_{b3},s_3\right)\right| \tag{39}$$

Where I_i is the obscuration time interval of the i-th smoke decoy projectile.

Beam Search Algorithm Framework

A phased beam search algorithm is adopted:

Initialization:

$$Beam_0=\left\{\left(\theta,v,\phi,\phi,\phi\right)\right\} \tag{40}$$

Phase expansion ($k=1,2,3$):

$$Beam_k = Top_K\left\{Beam_{k-1}\oplus\left(t_{bk},s_k\right)\right\} \tag{41}$$

Where $\oplus$ represents all possible combinations of adding one smoke decoy projectile,and Top_K retains the top K optimal solutions.

Local Search Parameter Settings

Coarse search grid parameters: heading angle: $\theta\in\left[\theta_0-60°，\theta_0+60°\right]$,15 points;flight speed: $v\in\left[70,140\right]m/s$,5 points;deployment time: $t_b\in\left[0,t_{end}\right]$,step size $0.20s$; fuze delay: $s\in\left[0.05,19.0\right]$,step size $0.10s$.

Fine search perturbation range: heading angle: $\theta\pm5°$,step size $1°$;flight speed: $v\pm10\,m/s$, step size $5\,m/s$;deployment time: $t_b\pm0.5s$,step size $0.1s$;fuze delay: $s\pm0.5s$,step size $0.1s$.

Obscuration Effect Evaluation Model

Adopt high-precision time discretization:

$$\Delta t=0.005s,t_{grid}=0:\Delta t:t_{end} \tag{42}$$

Geometric obscuration judgment:

$$d\left(\vec{P}_{cloud,i}\left(t\right),\vec{P}_m\left(t\right),\vec{P}_{t\arg et}\right)\le10m \tag{43}$$

Time Interval Processing Model

Interval merging operator:

$$merge(I)=\left\{\left[t_{start,k},t_{end,k}\right]\middle|\bigcup_{k}\left[t_{start,k},t_{end,k}\right]\right\} \tag{44}$$

Union calculation:

$$U=merge\left(I_1\bigcup I_2\bigcup I_3\right) \tag{45}$$

Total obscuration time:

$$T_{total}=\sum_{k=1}^{K}\left(t_{end,k}-t_{start,k}\right) \tag{46}$$

This model effectively solves the optimization problem in the 8-dimensional decision space via the beam search algorithm, obtaining an approximate global optimal solution while ensuring computational efficiency.

Solution of Models

Beam Search Coarse Search Stage

Using the beam search algorithm to perform global exploration in the parameter space:

Search parameter settings: heading angle range: $179.36^\circ \pm 60^\circ$,15 equally spaced points;flight speed range: $\left[70,140\right]m/s$,5 equally spaced points;deployment time range: $\left[0,\ t_{end}\right]s$,step size $0.20s$;fuze delay range: $\left[0.05,19.0\right]s$,step size $0.10s$.

Algorithm execution:

Beam size: $K=20$ (retain 20 optimal candidates per stage).Candidate screening: retain the top 80 candidate strategies per stage.Time step: $\Delta t=0.02s$ perform coarse-grained evaluation.A total of $15\times 5=75$ heading-speed combinations were computed to obtain the initial optimal solution: $T_{total}^{(0)}=6.210s$.

Local Perturbation Optimization Stage

Perform refined search near the coarse search optimal solution:

Perturbation Range Settings: Heading Angle: $179.36° \pm 5°$, step size $1°$; flight speed: $140.0 \pm 10 m/s$, step size $5 m/s$, deployment time: optimal value of each smoke decoy projectile $\pm 0.5s$, step size $0.1s$; fuze delay: optimal value of each smoke decoy projectile $\pm 0.5s$, step

size $0.1s$. Evaluate using a finer time step ($\Delta t = 0.005s$)to obtain the optimized solution: $T_{total}^{(1)} = 6.690s$.

Optimal Parameter Combination

Obtain the optimal parameters for maximizing obscuration time:

UAV Flight Parameters: optimal heading angle: $\theta^* = 179.36°$; optimal flight speed: $v^* = 140.0 m/s$.

Smoke decoy projectile 1 parameters: deployment time: $t_{b1}^* = 4.000s$; fuze delay: $s_1^* = 3.850s$; independent obscuration time: $4.040s$; relative deployment time: $t_{rel1} = 0.150s$.

Smoke decoy projectile 2 parameters: deployment time: $t_{b2}^* = 8.000s$; fuze delay: $s_2^* = 5.050s$; independent obscuration time: $2.380s$; relative deployment time: $t_{rel2} = 2.950s$.

Smoke decoy projectile 3 parameters: deployment time: $t_{b3}^* = 9.900s$; fuze delay: $s_3^* = 5.450s$; independent obscuration time: $0.570s$; relative deployment time: $t_{rel3} = 4.450s$.

Key Position Calculation

Calculate the detonation points of each smoke decoy projectile based on the optimal parameters.

Smoke decoy projectile 1 detonation point:

$$\begin{cases} x_{\det 1} = 17800 + 140.0 \times 4.000 \times \cos(179.36°) = 17176.8m \\ y_{\det 1} = 0 + 140.0 \times 4.000 \times \sin(179.36°) = 9.8m \\ z_{\det 1} = 1800 - \frac{1}{2} \times 9.8 \times 5.050^2 = 1675.0m \end{cases} \tag{47}$$

Smoke decoy projectile 2 detonation point:

$$\begin{cases} x_{\det 2}=17800+140.0\times 8.000\times\cos\left(179.36^{\circ}\right)=16553.6m \\ y_{\det 2}=0+140.0\times 8.000\times\sin\left(179.36^{\circ}\right)=19.6m \\ z_{\det 2}=1800-\frac{1}{2}\times 9.8\times 5.050^{2}=1675.0m \end{cases} \tag{48}$$

Smoke decoy projectile 3 detonation point:

$$\begin{cases} x_{\det 3}=17800+140.0\times 9.900\times\cos\left(179.36^{\circ}\right)=16241.9m \\ y_{\det 3}=0+140.0\times 9.900\times\sin\left(179.36^{\circ}\right)=24.3m \\ z_{\det 3}=1800-\frac{1}{2}\times 9.8\times 5.450^{2}=1654.5m \end{cases} \tag{49}$$

Coordinated Obscuration Effect

Total coordinated obscuration time of three smoke decoy projectiles: $6.690s$ .Obscuration interval distribution:smoke decoy projectile 1: $\left[t_{11},t_{12}\right]$, duration $4.040s$;smoke decoy projectile 2: $\left[t_{21},t_{22}\right]$, duration $2.380s$;smoke decoy projectile 3: $\left[t_{31},t_{32}\right]$, duration $0.570s$.

Union Calculation: $T_{total}=\left|I_1\bigcup I_2\bigcup I_3\right|=6.690s$.

High-Precision Verification: Perform discretization computation using a time step $\Delta t=0.005s$,the verification results are completely consistent.

Result Analysis

Deployment interval: $4.000s\rightarrow 8.000s\rightarrow 9.900s$;Compliance with minimum interval constraint of 1 s: $4.000s, 1.000s, 1.900s$; All detonation heights are greater than 0: $1727.4m, 1675.0m,\ 1654.5m$. Maximum obscuration time of a single projectile: $4.040s$ (smoke decoy projectile 1);Three-projectile coordinated obscuration time: $6.690s$;Coordination efficiency: $\frac{6.690}{4.040}=1.656$ times.The detonation points of the three smoke decoy projectiles are distributed along the missile trajectory,ranging from $17176.8m$ to $16241.9m$ in distance and from $1727.4m$ to $1654.5m$ in height, forming a good spatial gradient distribution. The results are shown in Figures 5 and 6.

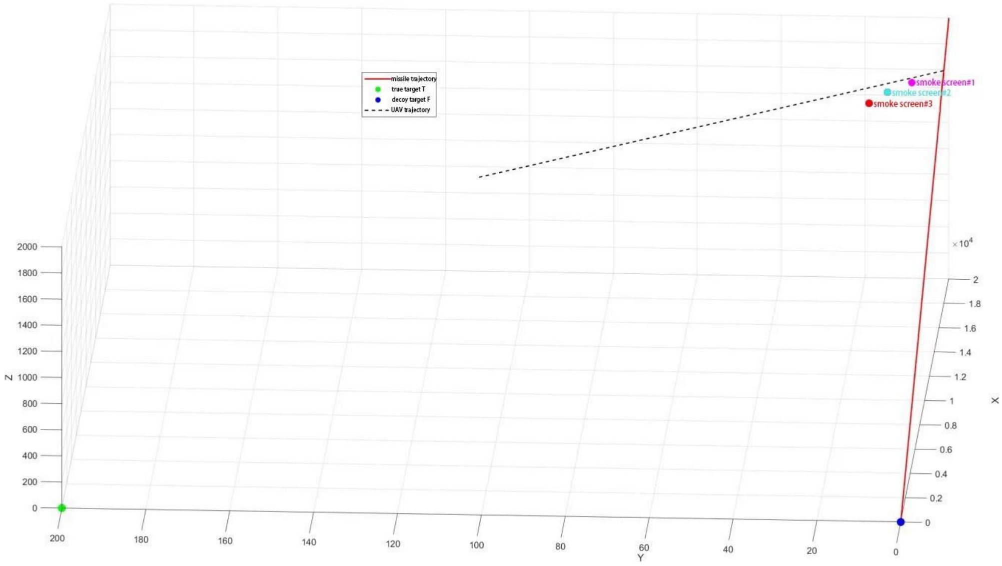

Figure 5. UAV, Missile and Smoke Cloud Detonation

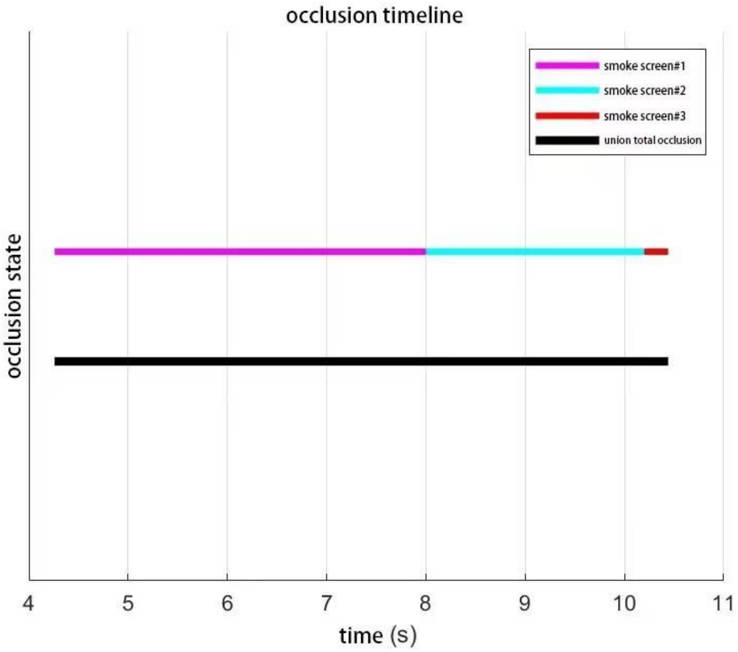

Figure 6. Obscuration Time and Status

RESEARCH ON MULTI-AIRCRAFT COOPERATIVE INTERFERENCE EFFECTIVENESS OPTIMIZATION BASED ON HIERARCHICAL OPTIMIZATION AND COMBINATORIAL ENUMERATION MODEL

Establishment of Models

Establishment of Multi-UAV Cooperative Optimization Framework

For the cooperative jamming problem of three UAVs (FY1, FY2, FY3), a hierarchical optimization framework is established:

Decision variables for each UAV:

$$\overrightarrow{X}_i = \left(v_i, \theta_i, t_{b,i}, s_i\right), i = 1,2,3 \tag{50}$$

Optimization objective: maximization of the union of obscuration times of three UAVs.

$$\max T_{total} = \left|\bigcup_{i=1}^{3} I_i\left(\overrightarrow{X}_i\right)\right| \tag{51}$$

Where I_i is the obscuration time interval generated by the i-th UAV.

Single-UAV Candidate Strategy Generation Model

Based on the single-UAV optimal solutions of each UAV $\overrightarrow{X}_i^*$,establish a local search space:

Heading angle search range:

$$\theta \in \left[\theta_i^* - 6°, \theta_i^* + 6°\right], \Delta\theta = 1.5° \tag{52}$$

Flight speed search range:

$$v_i \in \left[\max\left(70, v_i^* - 10\right), \min\left(140, v_i^* + 10\right)\right], \Delta v = 2.5 m/s \tag{53}$$

Deployment time search range:

$$t_{b,i} \in \left[\max\left(0, t_{b,i}^{*} - 1.5\right), \min\left(t_{end}, t_{b,i}^{*} + 1.5\right) \right], \Delta t_b = 0.25s \tag{54}$$

Fuze delay search range:

$$s_i \in \left[\max\left(0.05, s_i^{*} - 1.0\right), \min\left(s_{\max}, s_i^{*} + 1.0\right) \right], \Delta s = 0.2s \tag{55}$$

Where $s_{\max} = \sqrt{\frac{2z_{0,i}}{g}}$ is the maximum allowable fuze delay.

Physical Constraint Validation Model

Non-negativity constraint on deployment time:

$$t_{rel,i} = t_{b,i} - s_i \geq 0 \tag{56}$$

Positive constraint on detonation height:

$$z_{\det,i} = z_{0,i} - \frac{1}{2} g s_i^2 > 0 \tag{57}$$

Obscuration Effect Evaluation Model

Adopt high-precision time discretization:

$$\Delta t = 0.005s, t_{grid} = 0 : \Delta t : t_{end} \tag{58}$$

Geometric obscuration judgment condition:

$$d\left(\vec{P}_{cloud,i}(t),\vec{P}_m(t),\vec{P}_{target}\right)\le 10m \tag{59}$$

Time Interval Union Calculation Model

Define the time interval merging operator:

$$merge(I)=\left\{\left[t_{start,k},t_{end,k}\right]\middle|\bigcup_k\left[t_{start,k},t_{end,k}\right]\right\} \tag{60}$$

Union of obscuration times of three UAVs:

$$U=merge\Big(merge\left(I_1\bigcup I_2\right)\bigcup I_3\Big) \tag{61}$$

Total obscuration time:

$$T_{total}=\sum_{k=1}^{K}\left(t_{end,k}-t_{start,k}\right) \tag{62}$$

Combinatorial Optimization Enumeration Model

Assume each UAV retains $L=20$ candidate strategies, combinatorial enumeration: total number of combinations $=\prod_{i=1}^{3}L_i=20\times20\times20=8000$ .For each combination (i,j,k),calculate:

$$T_{total}(i,j,k)=\left|merge\left(I_{1,i}\bigcup I_{2,j}\bigcup I_{3,k}\right)\right| \tag{63}$$

Optimal Strategy Selection Model

Find the combination that maximizes the total obscuration time:

$$\left(i^*, j^*, k^*\right) = \underset{i,j,k}{\arg\max}\, T_{total}\left(i, j, k\right) \tag{64}$$

Optimal cooperative strategy:

$$\overrightarrow{X}^* = \left(\overrightarrow{X}_{1,i^*}, \overrightarrow{X}_{2,j^*}, \overrightarrow{X}_{3,k^*}\right) \tag{65}$$

This problem effectively solves the complex optimization problem of multi-UAV cooperative smoke decoy deployment through hierarchical optimization and combinatorial enumeration, obtaining an approximate global optimal solution while ensuring computational efficiency.

Solution of Models

Single-UAV Candidate Strategy Generation

Based on the single-UAV optimal solutions of each UAV, generate candidate strategies within the local parameter space:

FY1 candidate strategy generation:heading angle range: $179.36^\circ \pm 6^\circ$, step size 1.5°; flight speed range: $125.0 \pm 10\, m/s$, step size $2.5\, m/s$; deployment time range: $4.59 \pm 1.5s$, step size $0.25s$; fuze delay range: $3.85 \pm 1.0s$, step size $0.2s$.

FY2 candidate strategy generation:heading angle range: $-74.00^\circ \pm 6^\circ$, step size 1.5°; flight speed range: $105.0 \pm 10\, m/s$, step size $2.5\, m/s$; deployment time range: $13.50 \pm 1.5s$, step size $0.25s$; fuze delay range: $5.60 \pm 1.0s$, step size $0.2s$.

FY3 candidate strategy generation:heading angle range: $81.00^\circ \pm 6^\circ$, step size 1.5°; flight speed range: $125.0 \pm 10\, m/s$, step size $2.5\, m/s$; deployment time range: $25.00 \pm 1.5s$, step size $0.25s$; fuze delay range: $2.90 \pm 1.0s$, step size $0.2s$.

Each UAV retains the top 20 candidate strategies with the longest obscuration time.

Combinatorial Enumeration Optimization

Traverse all combinations of three-UAV candidate strategies, total number of combinations: $20\times 20\times 20=8000$ .Calculate the union of obscuration times of the three UAVs for each combination, evaluated using a high-precision time step of $\Delta t=0.005s$.

Optimal Cooperative Strategy

Obtain the optimal parameter combination for maximizing obscuration time:

FY1 optimal parameters:heading angle: $179.36°$;f light speed: $125.0\,m/s$; deployment time: $4.59s$; fuze delay: $3.85s$; independent obscuration time: $4.405s$.

FY2 optimal parameters:heading angle: $-74.00°$; flight speed: $105.0\,m/s$; deployment time: $13.50s$; fuze delay: $5.60s$; independent obscuration time: $4.580s$.

FY3 optimal parameters:heading angle: $81.00°$; flight speed: $125.0\,m/s$; deployment time: $25.00s$; fuze delay: $2.90s$; independent obscuration time: $4.775s$.

Coordinated Obscuration Effect

Total coordinated obscuration time of three UAVs: $T_{total}=T_1+T_2+T_3=4.405+4.580+4.775=13.760s$.

High-Precision Verification:

Using a time step of $\Delta t=0.005s$ for discretization computation, identical results are obtained: Total number of obscured points: 2752 points, total obscuration time: $2752\times 0.005=13.760s$.

Result Analysis

The independent obscuration times of the three UAVs are $4.405s$ 、 $4.580s$ 、 $4.775s$, respectively, with a total obscuration time of $13.760s$ .There is no overlap in time intervals, resulting in a fully additive effect. The hierarchical optimization framework finds the optimal cooperative strategy within a reasonable computation time, with the three-UAV obscuration time reaching $13.760s$, demonstrating the effectiveness of multi-UAV cooperative operations. The results are shown in Figures 7 and 8.

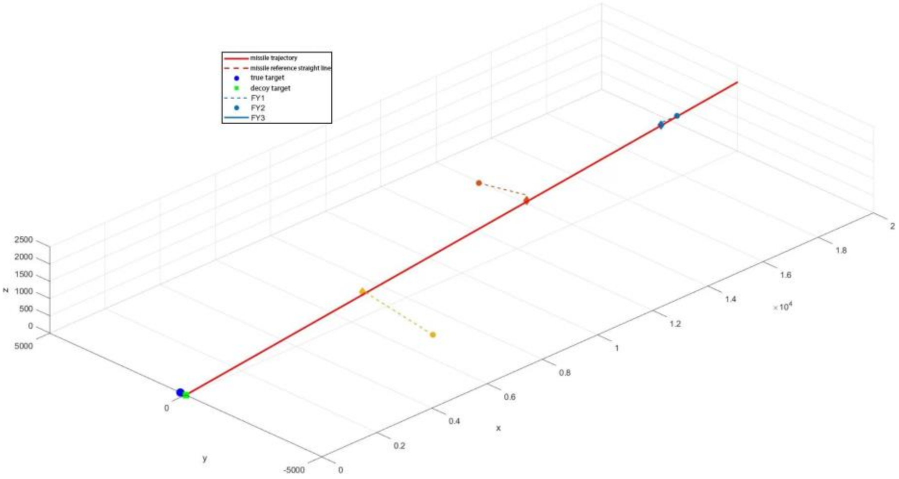

Figure 7. Three-UAV Joint Obscuration

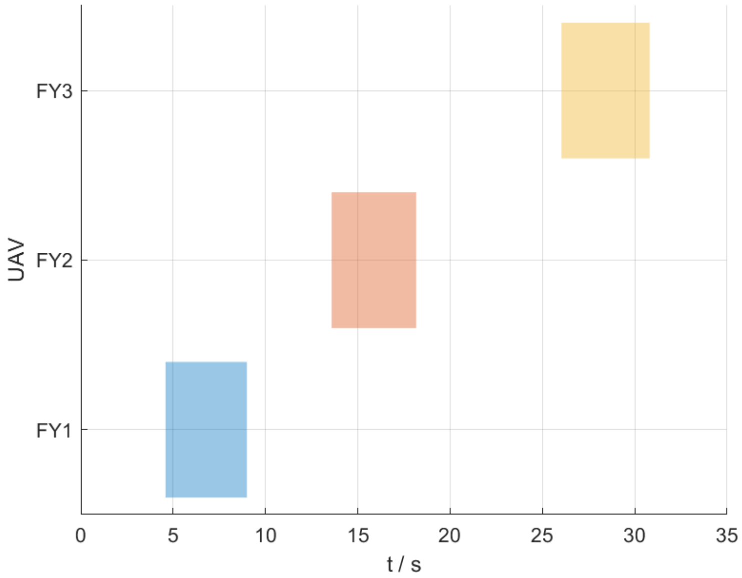

Figure 8. Three-UAV Obscuration Time Graph

CONCLUSIONS

This study addresses the complex temporal optimization problem of multi-UAV cooperative smoke decoy interference against missiles. By integrating kinematic modeling with the dynamic evolution characteristics of functional smoke materials, by constructing phased optimization and local refinement models, it systematically resolves a series of challenges ranging from single-UAV parameter optimization to multi-UAV cooperative decision-making. Based on accurate kinematic modeling and a dynamic evolution model of smoke clouds, a hierarchical cooperative optimization framework is innovatively proposed: at the single-projectile level, grid search and rapid evaluation methods are employed, with parameter optimization achieved through a coarse-fine combined strategy; at the multi-projectile cooperative level, an intelligent algorithm integrating Beam Search-based global exploration and local refinement adjustment is developed to effectively handle high-dimensional decision spaces; at the multi-UAV cooperative level, an efficient decision-making mechanism of "local candidate enumeration-global interval merging" is designed. The research results demonstrate that the established model system possesses both physical accuracy and computational efficiency. The optimization strategy proposed in this paper not only improves the efficiency of missile interception but also provides an important quantitative decision-making basis for the deployment of flexible shielding materials and functional fiber assembly in modern defense systems.” The above modification suggestions are provided for reference only and are intended to offer a possible pathway for integrating algorithmic models with textile science. You are encouraged to build upon this foundation by incorporating specific textile material theories—such as the influence of fiber fineness and aggregate porosity on extinction coefficients—to further enhance logical rigor and technical detail. The adopted high-precision time discretization and refined parameter adjustment methods ensure the accuracy of obscuration duration calculation, providing a complete theoretical and methodological system and practical technical tools for cooperative interference strategy planning in dynamic adversarial environments.

Author Contributions

All work was completed independently by the author. The author has read and agreed to the published version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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