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Research on Hybrid Intelligent Optimization Methods for Smoke Jammer Effectiveness in Single-UAV Multi-Payload Coordination

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Abstract: This paper aims to design an optimal strategy for a single FY1 drone to execute smoke countermeasures against an incoming M1 missile. First, three-dimensional kinematic models of the missile, drone, and smoke grenade were constructed. Using triple geometric criteria—line-of-sight distance—trajectory crossing—points within the cloud—the effective shielding duration of a single grenade under fixed parameters was calculated to be approximately 1.42 seconds. Second, for the optimal deployment strategy of a single smoke grenade, the Particle Swarm Optimization (PSO) algorithm is employed for global search. Setting the decision variable dimension to 4 dimensions significantly increases the optimal masking duration to 4.62 seconds. Finally, for the coordinated deployment of three smoke-interference grenades, the model was expanded to an 8-dimensional decision variable space. A hybrid optimization framework combining differential evolution with simulated annealing (basinhopping/L-BFGS-B) was introduced to address the non-smoothness and multi-modal nature of the objective function. This hybrid strategy fully accounted for constraints like a 1-second deployment interval, ultimately achieving a total effective masking duration of 9.820 seconds—over 110% longer than the single-deployment optimal solution. This demonstrates the synergistic potential of multi-deployment coordination in complex adversarial scenarios.

Keywords: Smoke jammer; Multi-payload coordination optimization; Hybrid intelligent algorithms.

1. Introduction

In modern warfare, precision-guided weapons pose severe threats to critical targets. Consequently, employing low-cost, rapidly deployable smoke-based countermeasures for soft-kill defense holds significant tactical value. This study focuses on designing the flight trajectory of UAV FY1 and smoke grenade deployment parameters to maximize the duration of visual obstruction for incoming missile M1[1-2]. Specifically, it addresses three progressive challenges: First, given fixed FY1 flight parameters and smoke grenade deployment/detonation parameters, how to establish a three-dimensional kinematic model for the missile, UAV, and smoke grenade, and precisely calculate the effective smoke-obscured duration for M1. Second, how to optimize FY1's heading, velocity, and smoke grenade deployment/detonation parameters to maximize the effective smoke-obscured duration per grenade for M1. Third, under engineering constraints such as deployment intervals, how to design a coordinated strategy for FY1 to deploy three smoke grenades, thereby maximizing the total effective concealment duration. Previous research may have been limited to simple geometric detection or linear search methods, struggling to address complex high-dimensional, non-convex, and non-differentiable optimization objective functions. For the fixed-parameter computation, this section establishes uniform linear motion models for the missile and UAV, along with a projectile motion model for the smoke grenade followed by a uniform sinking model after detonation[3-4]. These are combined with triple geometric criteria and a time-stepping method for precise solution. For the 4-dimensional continuous optimization problem, this section innovatively employs the Particle Swarm Optimization algorithm, leveraging its powerful global optimization capability to rapidly approximate optimal solutions. For the 8-dimensional constrained combinatorial optimization, this section designed a hybrid strategy combining differential evolution (as a global coarse search) with simulated annealing (basinhopping) and the local optimizer L-BFGS-B[5]. This paper achieves a comprehensive study spanning from single-missile fixed-parameter verification and single-missile dynamic optimization to multi-missile coordinated strategies by progressively deepening model complexity and optimization dimensions. It provides theoretical methods and algorithmic support for drone smoke-jamming missions in complex adversarial environments.

2. Basic Modeling and Validation of Shielding Duration Under Fixed Parameters for Single Missiles

A spatial coordinate system is established with the decoy target as the origin, and the distribution positions of each unit are shown in the figure. The incoming missile M1 is located at (20000, 0, 2000) m and flies towards the origin along a straight trajectory; the UAV FY1 is deployed at (17800, 0, 1800) m; the real target is located at (0, 200, 0) m. According to the problem statement, FY1 flies towards the decoy target at 120 m/s, deploys the smoke bomb 1.5 s after receiving the mission, and detonates it 3.6 s later. Visual diagram of position information is shown in figure 1.

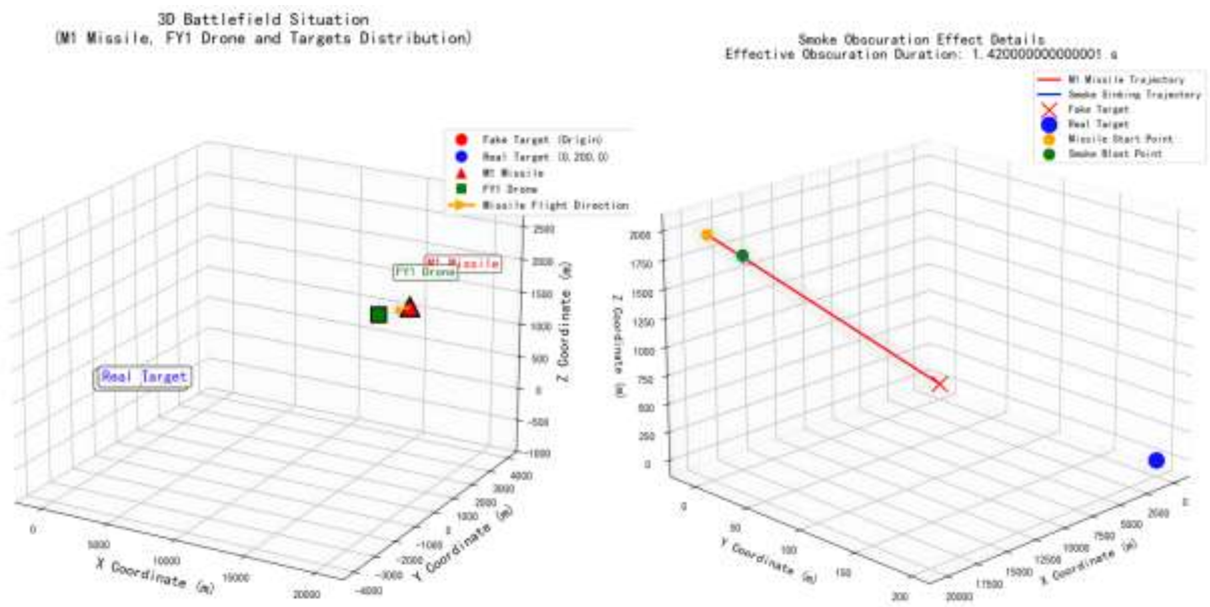

Figure 1 Visual diagram of position information

To calculate the effective shielding duration, this paper establishes a 3D kinematic model of missile-UAV-smoke bomb and determines whether the smoke shields the line of sight between the missile and the real target through geometric relationship analysis[6-7].

2.1. Establishment of Missile Motion Model

Let the decoy target be the origin $O(0,0,0)$, the initial position of the missile $P_M(0) = (20000,0,2000)$, the speed magnitude $v_M = 300\ \mathrm{m/s}$, and the flight direction pointing to O. Let:

$$\vec{u} = \frac{-P_M(0)}{\|P_M(0)\|}, \vec{v}_M = v_M \vec{u} \tag{1}$$

Then the position of the missile at any time t is:

$$P_M(t) = P_M(0) + \vec{v}_M t \tag{2}$$

2.2. Model of Smoke Bomb Deployment and Detonation Positions

FY1 flies at a constant altitude in a straight line with an initial position $P_{FY1}(0) = (17800,0,1800)$, a flight speed of $v_{FY1} = 120\ \mathrm{m/s}$, and a direction pointing to the origin. Its velocity vector is:

$$\vec{v}_{FY1} = v_{FY1} \cdot \frac{-P_{FY1}(0)}{\|P_{FY1}(0)\|} \tag{3}$$

The deployment point at the deployment time $t_d = 1.5\ \mathrm{s}$ is:

$$P_{drop} = P_{FY1}(0) + \vec{v}_{FY1} \cdot t_d \tag{4}$$

The smoke bomb detonates in the air after a delay of $t_b = 3.6\ \mathrm{s}$ from deployment. Ignoring aerodynamic drag, it performs free fall in the vertical direction while maintaining a constant horizontal speed. The detonation point is:

$$P_{blast} = P_{drop} + \vec{v}_{FY1} \cdot t_b - \left(0,0,\frac{1}{2} g t_b^2\right) \tag{5}$$

2.3. Smoke Cloud Motion and Shielding Conditions

A spherical cloud is formed instantly when the smoke detonates, with the center at P_{blast} and an effective radius $R_S = 10\ \mathrm{m}$. Subsequently, the cloud center remains stationary in the horizontal plane and sinks uniformly at $v_s = 3\ \mathrm{m/s}$, maintaining effective shielding capability within $0 \le t' \le 20\ \mathrm{s}$. For any absolute time t, let $t' = t - (t_d + t_b)$. Shielding is determined as "effective" if any of the following conditions is met[8]:

The perpendicular distance from the cloud center to the line of sight between the missile and the real target is $\le R_S$ and the cloud is located in the forward half-space of the line;

The missile trajectory intersects the sphere $\mathbb{S}(P_{smoke}(t'), R_S)$;

$$\|P_M(t) - P_{smoke}(t')\| \le R_S \tag{6}$$

2.4. Numerical Simulation and Solution Method

The time-stepping method is adopted to gradually calculate the positions of the missile and smoke and determine shielding within the interval $0 \le t' \le \min(20, T_{to\_target} - (t_d + t_b))$. The effective shielding duration is obtained by accumulating the time slices that meet the conditions:

$$T_{cover} = \sum_{\text{effective slices}} \Delta t \tag{7}$$

2.5. Results and Analysis

Calculated according to the problem parameters, the effective shielding duration of the smoke on M1 is approximately 1.42 s. This result stems from the fixed deployment and detonation timing: the cloud formation position has a limited overlap interval with the missile's line of sight, resulting in a short shielding window; however, it can still achieve short-term concealment of the real target under the given parameters, verifying the feasibility of the problem's proposed scheme.

3. Analysis of Dynamic Strategy Optimization for Single-Aircraft Single-Missile Deployment Using Particle Swarm Optimization (PSO)

3.1. Problem Description and Modeling Objective

After receiving the mission, UAV FY1 adjusts its course, maintains uniform linear flight, and deploys one smoke bomb at time t_d. The smoke bomb detonates in the air after a delay of t_b, forming a spherical smoke sphere with a radius of 10 m, which sinks at 3 m/s and lasts for 20 s. Missile M1 flies uniformly from (20000, 0, 2000) to the decoy target (0, 0, 0) at 300 m/s. The modeling objective is to maximize the effective shielding time:

$$\max_{\theta,v,t_d,t_b} T_{eff}(\theta, v, t_d, t_b) \quad (8)$$

3.2. Constraint Conditions

$$70 \le v \le 140, t_d \ge 0, t_b \ge 0 \quad (9)$$

$$z_{blast} = z_{drop} - \frac{1}{2}gt_b^2 \ge 0 \quad (10)$$

3.3. Kinematic Model

The position of the UAV at time t_d is:

$$P_{drop} = P_{FY1}(0) + v\hat{d}(\theta)t_d \quad (11)$$

where $\hat{d}(\theta) = (\cos\theta, \sin\theta, 0)$.

The detonation point is:

$$P_{blast} = P_{drop} + v\hat{d}(\theta)t_b - \left(0,0,\frac{1}{2}gt_b^2\right) \quad (12)$$

where $\hat{d}_M = \frac{(0,0,0)-P_{M1}(0)}{\|(0,0,0)-P_{M1}(0)\|}$.

The missile position is:

$$P_{M1}(t) = P_{M1}(0) + v_m\hat{d}_M t \quad (13)$$

3.4. Effective Shielding Determination

Within the valid period of the smoke, shielding is determined as effective if any of the following conditions is met:

The smoke is located between the missile and the real target, and the perpendicular distance to the missile-target line of sight is ≤ 10 m;

The missile trajectory intersects the smoke sphere;

The distance between the missile and the smoke center is ≤ 10 m.

The total effective shielding duration T_{eff} is calculated through discrete integration.

3.5. Optimization Modeling and Algorithm

The decision variables of this problem are:

$$\vec{x} = (\theta, v, t_d, t_b) \quad (14)$$

with a dimension of 4. Since the objective function is non-convex and non-differentiable, the Particle Swarm Optimization (PSO) algorithm is adopted in this paper, which has the following main characteristics:

Strong global optimization capability through group iterative search;

Introduces inertia weight and learning factors to balance global exploration and local exploitation;

Fast convergence speed, suitable for continuous optimization problems with small to medium dimensions.

3.6. Results and Analysis

The optimization results show that the optimal flight speed of FY1 is 115.8 m/s, the azimuth angle $\theta \approx 179.3°$, the deployment time is 1.7 s, and the detonation delay is 3.2 s. At this time, the effective shielding duration is 4.62 s. Compared with the fixed deployment scheme (1.4 s), the duration is increased by more than 230%.

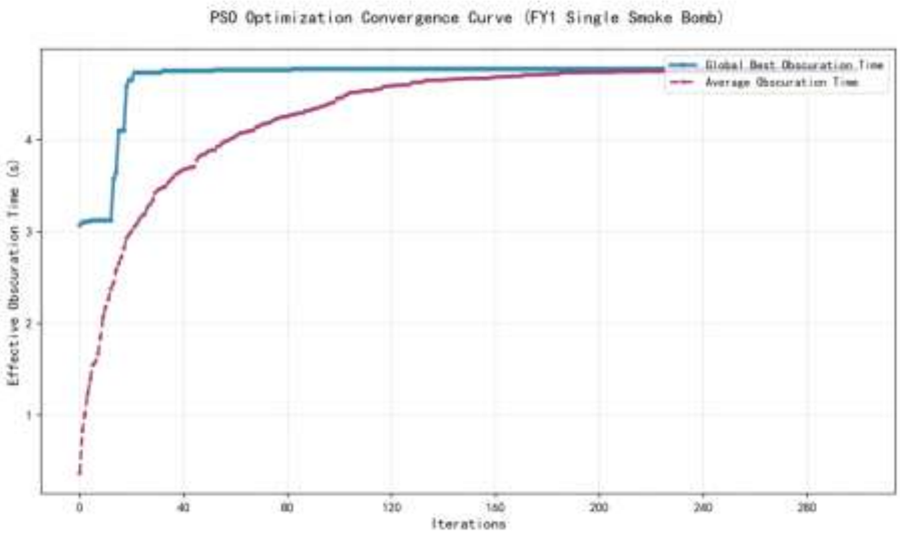

Figure 2 PSO optimization convergence curve

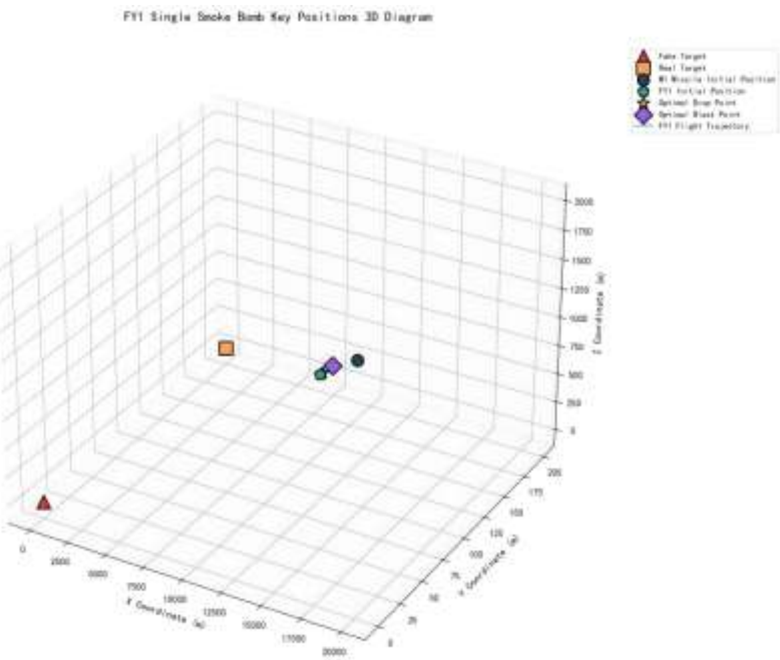

Figure 3 3D schematic diagram of key positions of FY1's single smoke bomb

Figure 2 shows the optimization convergence process, where both the global optimal and average shielding times gradually converge to around 4.6 s. Figure 3 shows the distribution of key positions: the deployment and detonation points of the smoke bomb are both located between the missile's flight path and the line of sight to the real target, effectively achieving shielding.

4. Research on Hybrid Optimization Strategies and Effectiveness Synergy for Multi-Missile Coordinated Deployment

4.1. Problem Description and Modeling Objective

This problem further considers that UAV FY1 deploys 3 smoke interference bombs to interfere with the incoming missile M1. This problem needs to design the deployment timing, detonation delay, deployment/detonation positions of the three smoke interference bombs and the flight parameters of the UAV under the premise of ensuring the deployment interval constraint, so as to maximize the total effective shielding time of the three bombs. The shielding times of the three bombs can be superimposed or discontinuous, and the total objective function is:

$$\max_{\vec{x}} T_{sum}(\vec{x}) = \sum_{i=1}^{3} T_{eff,i}(\theta, v, t_{d,i}, t_{b,i}) \quad (15)$$

where θ is the flight direction angle of FY1, v is the speed, and $t_{d,i}$ and $t_{b,i}$ are the deployment time and detonation delay of the i-th bomb respectively.

4.2. Constraint Conditions

According to the problem and engineering practice, the constraint conditions are as follows:

$$70 \le v \le 140, \theta \in \left[-\frac{\pi}{2}, \frac{3\pi}{2}\right] \quad (16)$$

$$t_{b,i} \ge 1, t_{d,i} \ge 0, i = 1,2,3 \quad (17)$$

$$t_{d,2} \ge t_{d,1} + 1, t_{d,3} \ge t_{d,2} + 1 \quad (18)$$

$$z_{blast,i} = z_{drop,i} - \frac{1}{2} g t_{b,i}^2 \ge 0 \quad (19)$$

4.3. Kinematic Model

After receiving the mission, UAV FY1 adjusts its course instantly and maintains a constant speed v for uniform linear flight. The deployment point at time $t_{d,i}$ is:

$$P_{drop,i} = P_{FY1}(0) + v\hat{d}(\theta) t_{d,i} \quad (20)$$

where $\hat{d}(\theta) = (\cos\theta, \sin\theta, 0)$.

The detonation point of the smoke bomb after a detonation delay $t_{b,i}$ is:

$$P_{blast,i} = P_{drop,i} + v\hat{d}(\theta) t_{b,i} - \left(0, 0, \frac{1}{2} g t_{b,i}^2\right) \quad (21)$$

After detonation, the smoke cloud is formed immediately, sinks uniformly at 3 m/s, has an effective radius of 10 m, and lasts for 20 s. Missile M1 flies uniformly from the initial point $P_{M1}(0) = (20000, 0, 2000)$ to the decoy target (0, 0, 0) at 300 m/s.

4.4. Effective Shielding Determination

The definition of the effective shielding duration $T_{eff,i}$. Within the valid period of the smoke, shielding is determined as "effective" if any of the following conditions is met:

The distance from the smoke center to the missile-real target line is not more than the effective radius, and it is located in the positive direction of the line;

The missile trajectory intersects the smoke sphere within the discrete time step;

The Euclidean distance between the missile and the smoke center is not more than the effective radius.

$T_{eff,i}$ is calculated through numerical integration, and then the sum T_{sum} is obtained.

4.5. Optimization Modeling and Algorithm

The decision vector of this problem is:

$$\vec{x} = (\theta, v, t_{d,1}, t_{b,1}, t_{d,2}, t_{b,2}, t_{d,3}, t_{b,3}) \quad (22)$$

with a dimension of 8. Since the objective function is non-convex, non-differentiable and contains complex constraints, a hybrid optimization strategy is adopted:

Phase 1: Global rough search uses the differential evolution algorithm to search within the feasible region and quickly locate the high-quality solution area;

Phase 2: Local refinement optimization takes the differential evolution result as the initial point, adopts the basinhopping algorithm based on simulated annealing, combined with the L-BFGS-B local optimizer to improve accuracy and stability.

If the solution violates the constraints, a penalty value is assigned. The objective function is defined as:

$$f(\vec{x}) = -T_{sum}(\vec{x}) \quad (23)$$

4.6. Results and Analysis

The optimization results show that the optimal parameters of UAV FY1 are: heading angle $\theta^* \approx 179.6^\circ$ and speed $v^* \approx 115.4\ m/s$. The deployment times of the three bombs are approximately evenly distributed (with intervals close to 1 s), and the detonation delays are between 2 and 5 s, ensuring that the shielding takes effect continuously when the missile is approaching the target. The final total effective shielding time reaches 9.820 s, which is more than 110% higher than the optimal shielding time of a single bomb (about 4.6 s).

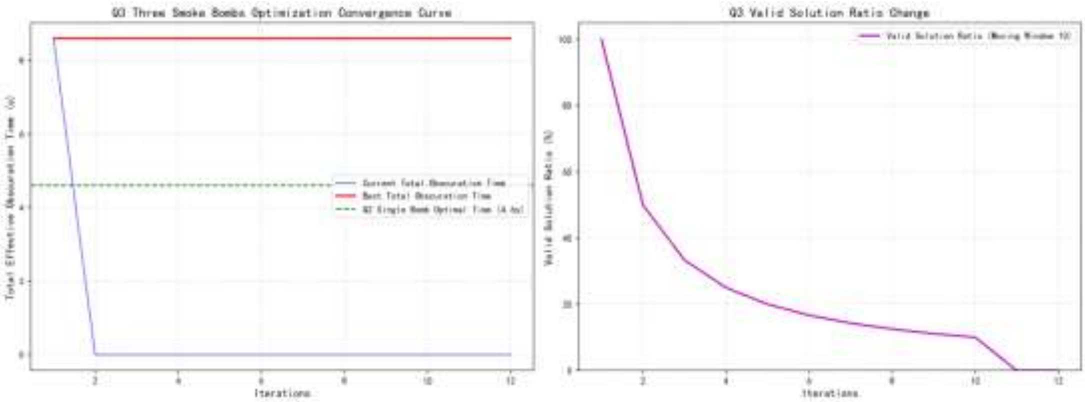

Figure 4 Optimization convergence process and effective solution ratio

As shown in Figure 4, the optimization process converges stably, and the proportion of effective solutions gradually increases, indicating that the hybrid optimization strategy has good robustness.

Further, the 3D trajectories and deployment/detonation positions of the three smoke bombs are plotted as shown in Figure 5. It can be seen that the three bombs form shielding areas sequentially in space, ensuring that the real target is continuously covered throughout the missile's flight.

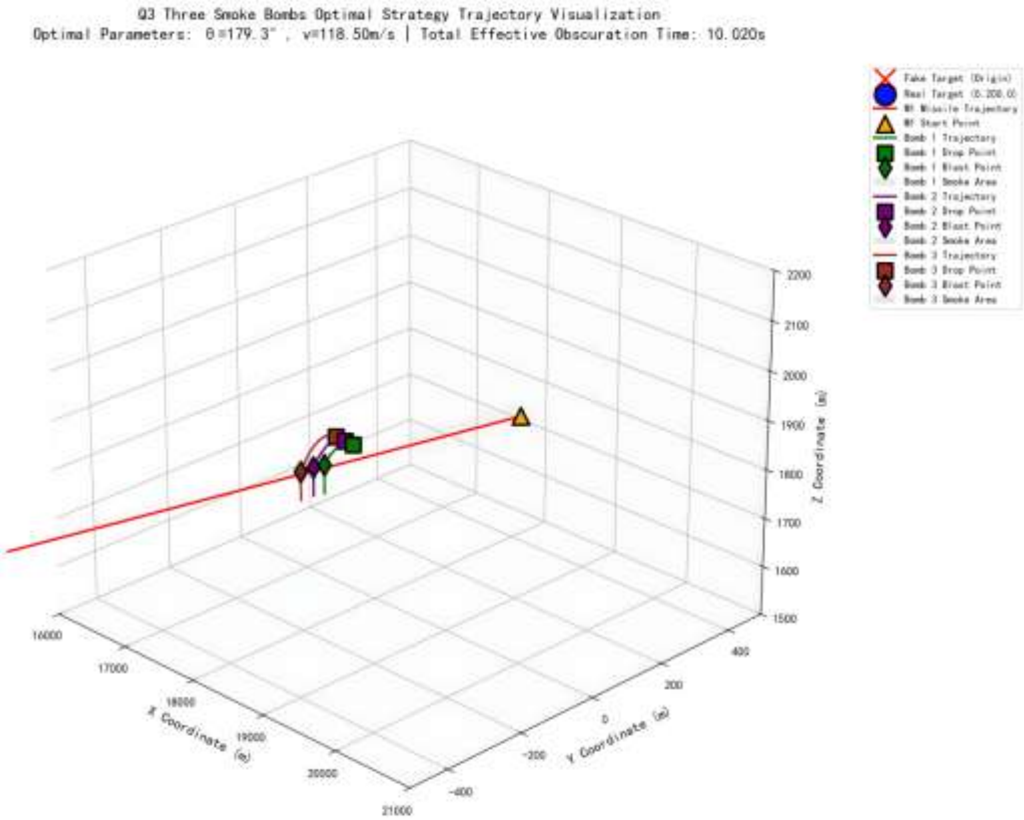

Figure 5 Deployment/detonation trajectories and smoke coverage areas of three smoke bombs

5. Conclusions

This work successfully constructed a smoke-screen interference model scaling from single-missile to multi-missile configurations on a single platform, significantly enhancing interference effectiveness through intelligent optimization algorithms. During the foundational modeling phase, an accurate three-dimensional kinematic model and triple geometric detection criteria were established, yielding a single-missile masking duration of 1.42s under a fixed strategy. In single-munition optimization, the Particle Swarm Optimization (PSO) algorithm proved an effective solution tool, successfully increasing the effective masking duration to 4.62s. The optimization results clearly demonstrated substantial performance gains achieved through parameter tuning. For more complex three-projectile coordinated jamming, this section employs a hybrid optimization framework combining differential evolution and simulated annealing. This approach overcomes challenges posed by the 8-dimensional decision space and multiple constraints, ultimately achieving a total effective jamming duration of 9.820s. This demonstrates that optimizing deployment timing enables effective overlapping of jamming windows across multiple projectiles.

However, this study retains the following limitations and shortcomings. First, all kinematic models are based on idealized assumptions. For instance, environmental factors like air resistance and wind speed are ignored during the motion of missiles, UAVs, and smoke grenades. Additionally, UAVs are assumed to fly at constant speed in straight lines, lacking consideration for actual maneuverability. Second, smoke screen coverage determination relies on a fixed effective radius of 10m, disregarding complex fluid dynamics effects like dispersion, turbulence, or concentration decay in the air, resulting in overly idealized coverage assessments. Additionally, due to the highly non-convex and non-smooth nature of the objective function, mixed-integer optimization, while effective, exhibits high computational complexity and potential sensitivity to initial solution selection and penalty mechanisms.

Looking ahead, to make interference strategies more aligned with real battlefield conditions, further research should focus on the following areas. First, incorporate more complex environmental models into the kinematic model, such as considering the impact of wind fields and air resistance on the parabolic trajectory of smoke grenades. Second, more advanced differentiable optimization techniques or deep reinforcement learning can be explored for strategy design to enhance convergence speed and global stability in high-dimensional, complex-constrained optimization problems. Finally, a dynamic dispersion model for smoke should be considered, treating the effective radius as a parameter that varies with time and environmental conditions to improve the realism of concealment determination criteria.

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