

Cooperative Optimization of Multi-UAV Smoke Screen Deployment Based on Obscuration Cone Model

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Abstract. Aiming at the "multi-UAV-single missile" smoke screen jamming mission in complex battlefield environments, this paper proposes a three-UAV cooperative deployment optimization method based on the Obscuration Cone Model. By constructing the kinematic models of the missile, UAVs and smoke cloud, a geometric judgment equation of the obscuration cone is established, and the Differential Evolution Algorithm is adopted to solve the nonlinear optimization model containing 12 decision variables. The study presents a heuristic heading angle constraint screening strategy to reduce the search space with high precision (0.1 degrees angle, 0.001 seconds time step). Simulation results show that the method significantly improves the target obscuration duration, with a total effective obscuration time of 11.714 seconds, an increase of approximately 150% compared with the single-UAV strategy. The results verify the effectiveness of the Obscuration Cone Model and the cooperative optimization algorithm in tactical-level protection.

Keywords: Obscuration Cone Model, Multi-UAV Coordination, Smoke Screen Jamming, Heuristic Constraints, Differential Evolution Algorithm.

1. Introduction

In modern battlefields, smoke screen jamming is an important passive defense method that can effectively reduce the infrared and optical guidance accuracy of incoming missiles. With the development of unmanned aerial vehicle (UAV) swarm cooperative control and precise deployment technology, achieving dynamic obscuration through multi-UAV coordination has become an efficient and flexible protection method [1,2]. Existing studies mainly focus on path planning, task assignment, and swarm control, such as multi-UAV cooperative path optimization [3], game-driven tactical evasion [4], and cooperative planning algorithms based on Differential Evolution [5]. However, research on precise obscuration judgment based on geometric obscuration cones and its coupled optimization with deployment strategies is relatively insufficient.

By constructing a judgment model of the "obscuration cone-target geometric relationship", this paper models multi-UAV cooperative deployment as a constrained high-dimensional optimization problem, and achieves optimal solution by combining heuristic constraints with the Differential Evolution Algorithm.

The study aims to quantitatively analyze the time-varying obscuration characteristics produced by multiple UAV smoke-screen releases and to establish a general evaluation model applicable to dynamic defense tasks. Through the "obscuration cone" mechanism, the visibility relationship between the missile line of sight and the target is described geometrically, allowing the continuous coverage process to be expressed as a measurable optimization objective. Compared with empirical or simulation-only methods, this analytical model improves both precision and computational efficiency.

To address the challenges of high dimensionality and nonlinear constraints in multi-UAV coordination, a heuristic heading-angle constraint method is proposed to narrow the search space before optimization, ensuring fast convergence without sacrificing global optimality. Then, a Differential Evolution-based algorithm is applied to determine the optimal release timing, locations, and trajectory parameters for each UAV. This approach integrates geometric modeling with intelligent optimization, forming a complete cooperative deployment framework that is suitable for real-time decision-making under complex battlefield conditions.

The research contributes in three main aspects. First, it introduces an explicit missile-centric obscuration evaluation model that can quantify smoke-screen effectiveness at any given time. Second, it provides an efficient heuristic-optimization coupling mechanism to handle multi-constraint cooperative deployment problems. Third, it offers a systematic foundation for designing and verifying smoke-screen defense strategies, thus enhancing the adaptive and continuous protection capabilities of UAV swarms against guided missile threats.

2. Research Methodology

2.1. Data Sources and Scenario Settings

The scenario data in this study are derived from a standardized tactical scenario, with its core parameters being typical and representative. The specific settings are as follows:

Scenario Source: This scenario setting simulates a typical asymmetric confrontation. The missile flies straight toward the decoy target located at the origin, and the high-maneuverability UAV platform needs to protect a static high-value real target from attacks by high-speed incoming missiles by releasing smoke screens to block the line of sight. All parameters such as initial positions, speeds, and geometric dimensions are within tactically reasonable ranges.

Parameter Characteristics:

Confrontational Nature: The scenario includes clear offensive and defensive sides with distinct optimization objectives.

High Dynamicity: All entities move at high speeds in 3D space, and their relative geometric relationships change rapidly over time.

High Dimensionality: There are 12 decision variables in total, forming a complex high-dimensional continuous optimization space.

Specific Parameters:

Missile (M): Initial position $P_M(0) = (20000, 0, 2000)$, speed $v_M = 300$ m/s, flying straight toward the origin of coordinates.

True Target (T): Vertical cylinder with center position $P_{TC} = (0, 200, 5)$, radius $R_T = 7$ m and height $H_T = 10$ m.

Unmanned Aerial Vehicles (UAVs): Three UAVs in total (FY_1, FY_2, FY_3) with initial positions $(17800, 0, 1800)$, $(12000, 1400, 1400)$, and $(6000, -3000, 700)$ respectively. Flight speed range $v_{FY} \in [70, 140]$ m/s

Smoke Screen Projectile: After detonation, it forms a spherical smoke screen with radius $R_{cloud} = 10$ m and effective duration $T_{effect} = 20$ s, descending vertically at $v_{descent} = 3$ m/s during the effective period. The complete list of scenario parameters used in simulations is summarized in Table 1.

Table.1. Complete Parameter Table of the Tactical Scenario

Entity Category	Parameter Name	Symbol	Value/Range	Unit
Missile	Initial Position	$P_M(0)$	(20000,0,2000)	-
	Flight Speed	v_M	300	m/s
True Target	Center Position	P_{TC}	(0,200,5)	-
	Radius	R_T	7	m
	Height	H_T	10	m
UAV (3 in total: FY ₁ , FY ₂ , FY ₃)	Initial Position (FY ₁)	$P_{FY_1}(0)$	(17800,0,1800)	-
	Initial Position (FY ₂)	$P_{FY_2}(0)$	(12000,1400,1400)	-
	Initial Position (FY ₃)	$P_{FY_3}(0)$	(6000, -3000,700)	-
	Flight Speed Range	v_{FY_j}	[70,140]	m/s
	Heading Angle	α_j	Tactically reasonable range	°
Smoke Screen Projectile	Deployment Time (by UAV _j)	$t_{drop,j}$	Tactically reasonable range	s
	Fuse Duration	$t_{fuse,j}$	Tactically reasonable range	s
	Smoke Screen Radius	R_{cloud}	10	m
	Effective Duration	T_{effect}	20	s
	Vertical Descent Speed	$v_{descent}$	3	m/s
Obscuration Cone	Missile-Cloud Distance	$D_j(t)$	Calculated by Eq. (4)	m
	Cone Half-Apex Angle	$\theta_{cone,j}(t)$	Calculated by Eq. (5)	°
	Obscuration Cone Volume	$V_{shield,j}(t)$	Defined by Eq. (6)	-
	Cone Axis Unit Vector	$d_j(t)$	$(P_{cloud,j}(t) - P_M(t)) / D_j(t)$	-
	Target Area	S_o	Cylindrical surface of the true target	-

The kinematic equations of the missile and UAVs are respectively:

$$P_M(t) = P_M(0) + v_M t \quad (1)$$

$$P_{FY_j}(t) = P_{FY_j}(0) + v_{FY_j} t \quad (2)$$

The coordinates of the detonation point after the jamming projectile is deployed are:

$$P_{det,j} = P_{FY_j}(t_{drop,j}) + v_{FY_j} t_{fuse,j} - \frac{1}{2} g t_{fuse,j}^2 \quad (3)$$

2.2. Obscuration Cone Model

(1) Geometric Definition of the Obscuration Cone

The obscuration cone is a rotational conical surface with the missile as the apex and the smoke cloud as the spherical matrix [6]. The missile position serves as the cone apex $P_M(t)$, the smoke cloud center is $P_{cloud,j}(t)$, and its radius is R_{cloud} . The distance from the missile to the smoke cloud center is calculated as follows:

$$D_j(t) = |P_M(t) - P_{cloud,j}(t)| \quad (4)$$

The half-apex angle of the obscuration cone is defined as:

$$\sin(\theta_{cone,j}) = \frac{R_{cloud}}{D_j(t)} \quad (5)$$

The equation of the obscuration cone is expressed as:

$$V_{shield,j}(t) = \{P \mid (P - P_M(t)) \cdot d_j \geq |P - P_M(t)| \cos(\theta_{cone,j})\} \quad (6)$$

where $d_j = \frac{P_{cloud,j}(t) - P_M(t)}{D_j(t)}$ is the unit vector in the direction of the cone axis.

(2) Target Obscuration Judgment

Let the true target area be denoted as S_O . If the target set is completely within the union of the obscuration cones formed by the three UAVs:

$$S_O \subseteq \bigcup_{j=1}^3 V_{shield,j}(t) \tag{7}$$

then the target is considered completely obscured at time [7].

The target obscuration duration is defined as:

$$T_{covered} = \int_0^T I \left(S_O \subseteq \bigcup_{j=1}^3 V_{shield,j}(t) \right) dt \tag{8}$$

A 3D schematic illustrating the tactical scenario of three UAVs (FY_1, FY_2, FY_3) deploying smoke screens to obscure a real target from an incoming missile. The missile travels towards a decoy target at the origin, while the UAVs fly on different paths to release smoke projectiles ("Unfused bomb") that form spherical smoke clouds ("cloud") to block the missile's line of sight to the real target. Figure 1 illustrates the spatial relationship among the three UAVs, the smoke clouds and the incoming missile used throughout this paper.

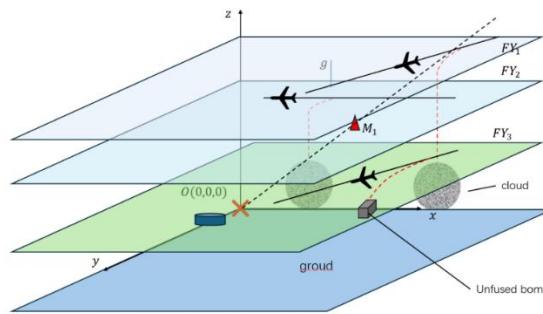


Figure 1. Schematic Diagram of Spatial Relative Positions between Three UAVs and a Missile

3. Cooperative Optimization Model and Solution Method

3.1. Construction of the Optimization Model

The decision variables of the three UAVs are defined as a matrix:

$$X = \begin{pmatrix} v_{FY_1} & \alpha_1 & t_{drop,1} & t_{fuse,1} \\ v_{FY_2} & \alpha_2 & t_{drop,2} & t_{fuse,2} \\ v_{FY_3} & \alpha_3 & t_{drop,3} & t_{fuse,3} \end{pmatrix} \in R^{3 \times 4} \tag{9}$$

The optimization objective is:

$$\max_X T_{covered}(X) \tag{10}$$

The constraints include speed, time, detonation height and geometric constraints:

$$\begin{cases} 70 \leq v_{FY_j} \leq 140 \\ t_{drop,j} \geq 0, t_{fuse,j} \geq 0 \quad j = 1,2,3 \\ Z_0 - \frac{1}{2}gt_{fuse,j}^2 > 0 \end{cases} \tag{11}$$

Z_0 is the vertical coordinate of the missile's initial position.

3.2. Heuristic Heading Angle Constraint Modeling

To improve computational efficiency, a high-precision heuristic constraint screening strategy [7] is adopted.

This method takes the missile-target line as the reference axis, gradually narrows the feasible region by simulating and calculating the matching degree between the heading angle and occlusion capability.

- (1) Traverse the heading angle with a step size of 0.1° ;
- (2) For each angle, simulate UAV flight with a time step of $\Delta t = 0.001s$;
- (3) Record the time interval when the occlusion judgment formula (7) is first satisfied;
- (4) The angle is feasible if there exists an effective occlusion time period.

Finally, the constraint range of the heading angle is obtained:

$$\begin{cases} 0.0^\circ \leq \alpha_1 \leq 180.8^\circ \\ 217.1^\circ \leq \alpha_2 \leq 308.2^\circ \\ 73.2^\circ \leq \alpha_3 \leq 129.0^\circ \end{cases} \quad (12)$$

The heuristic heading-angle screening procedure is summarized in Figure 2.

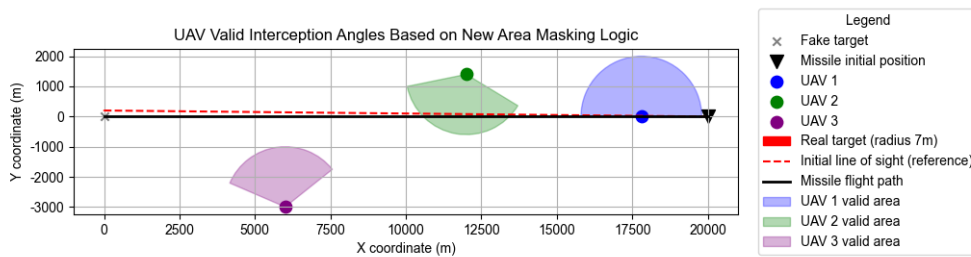


Figure 2. Flowchart of Heuristic Heading Angle Screening and Constraint Extraction

This plot displays the feasible heading angle areas for each UAV, determined by a heuristic screening strategy with a precision of 0.1° . The colored zones represent the valid flight directions for each UAV to achieve effective obscuration. The missile's initial position and its flight path towards the fake target are shown as a reference line.

3.3. Solution Using Differential Evolution Algorithm

The model solution employs the Differential Evolution (DE) algorithm [8]. DE achieves global optimization through differential mutation, crossover, and selection, making it particularly suitable for continuous nonlinear optimization problems. The algorithm consists of two stages:

- (1) Decoupled Pre-optimization: Each UAV is optimized independently to form a high-quality initial population.
- (2) Coupled Fine-optimization: Parameters are jointly adjusted under the global model to maximize the total coverage time.

4. Numerical Simulation and Experimental Analysis

4.1. Parameter Settings and Results

Simulation parameters and flight constraints are set according to tactical specifications [9]. The optimal strategy parameters for each UAV obtained by the Differential Evolution solver are listed in Table 2.

Table 2. Optimal Strategy Parameters for UAVs

UAV ID	Heading Angle	Velocity	Release Time	Fuse Duration	Coverage Duration
FY1	5.1°	125.92m/s	0.71s	0.28s	4.59s

FY2	301.1°	137.44m/s	6.79s	4.77s	3.98s
FY3	75.6°	139.14m/s	21.29s	1.66s	3.15s

The total effective coverage time achieved by the three-UAV cooperative deployment is: $T_{covered}^{max} = 11.714$ s.

Figure 3 shows the overall Differential Evolution workflow used for optimization, and Figure 4 presents the coverage-duration convergence curve across iterations.

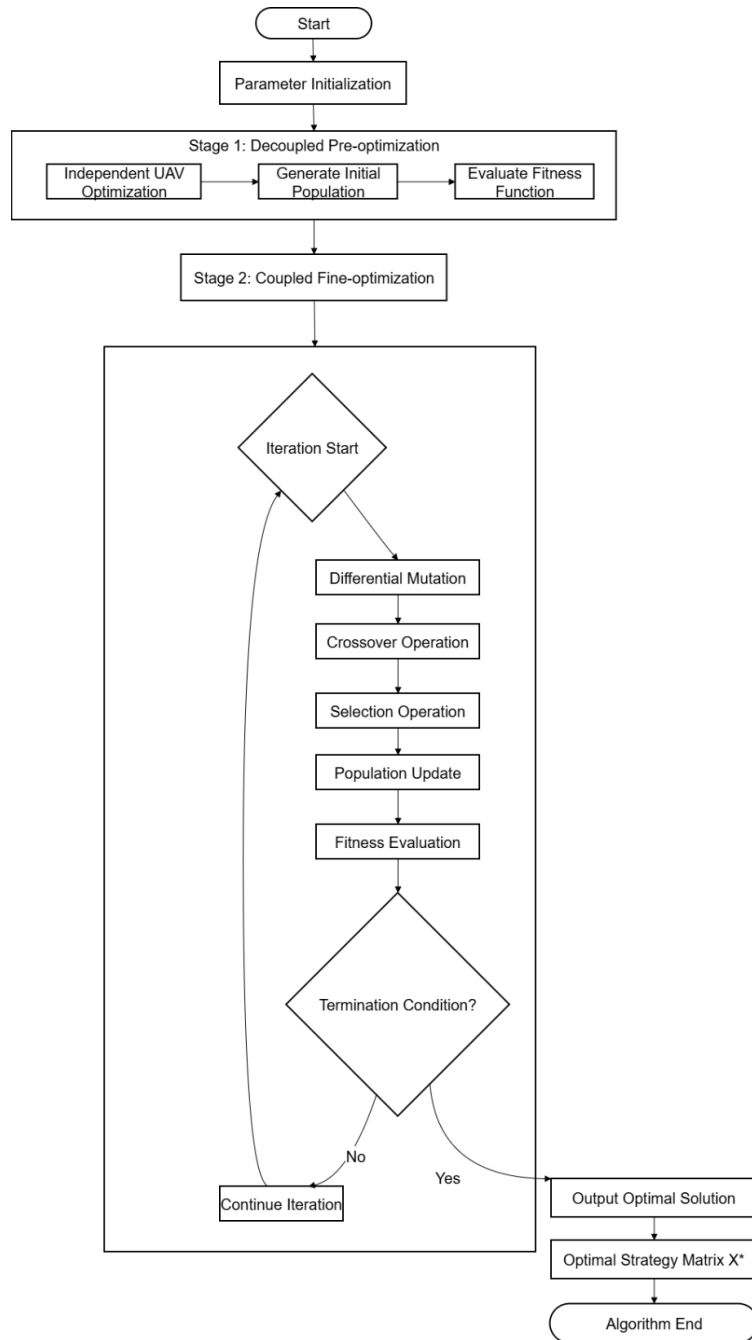


Figure 3. Overall Flowchart of the Differential Evolution Algorithm

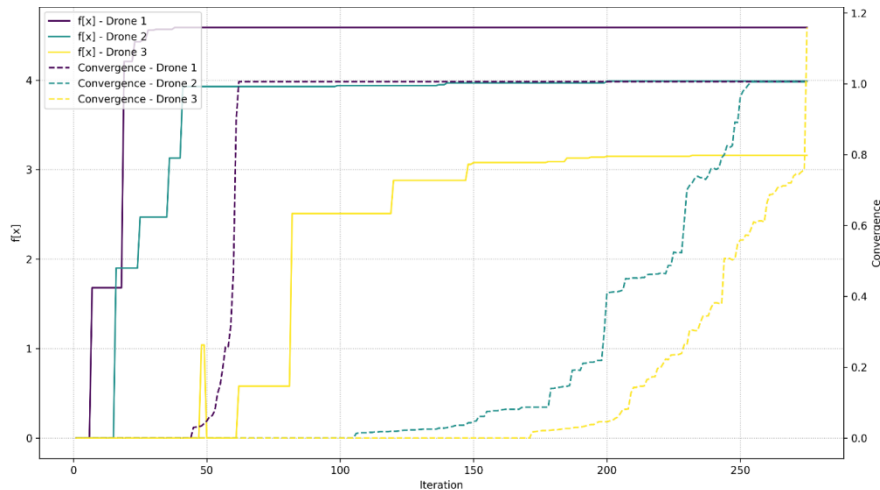


Figure 4. Coverage Duration Convergence Curve

Convergence plot of the Differential Evolution algorithm, showing the optimization of coverage duration ($f[x]$, solid lines) for each of the three drones over iterations. The dashed lines illustrate the convergence progress for each drone's strategy. The algorithm successfully maximizes the objective function for each UAV, leading to a synergistic cooperative engagement.

4.2. Results Analysis

The three UAVs, through differentiated heading angles and coordinated timing, enable the smoke clouds to achieve continuous relay coverage of the target in both time and space. The temporal coverage pattern described above corresponds to the parameter set in Table 2 and the convergence behaviour shown in Figure 4.

It is evident that the first UAV undertakes the initial coverage, the second provides protection during the middle phase, and the third offers compensatory coverage at the end. Together, they form a combined coverage cone with maximum overlap [10].

Compared to the single-UAV optimal deployment (approximately 4.58 s), the cooperative strategy achieves an improvement of about 150% (from 4.58 s to 11.714 s). This demonstrates that the proposed optimization framework can fully utilize the geometric characteristics of coverage to maximize spatiotemporal coverage.

5. Conclusion and Prospects

This paper presents a cooperative smoke-screen deployment strategy for multiple UAVs based on the “obscuration cone–target” geometric model and the Differential Evolution optimization method. The proposed approach establishes a precise obscuration relationship between missile viewpoint and target area, integrates a heuristic heading-angle constraint to simplify the optimization process, and effectively improves the overall obscuration performance of the system. Numerical simulations demonstrate that the multi-UAV cooperative strategy significantly extends the effective coverage duration compared with traditional single-UAV deployment, verifying the feasibility and efficiency of the method.

This research involves comprehensive modeling and algorithmic work, including geometric derivation, parameter discretization, and multi-dimensional optimization. The developed method is suitable for tactical mission planning and can be embedded into UAV cooperative control systems to support real-time decision-making in defensive operations.

Future work will focus on refining the smoke diffusion model by considering wind field and environmental disturbances, as well as extending the framework to multi-objective optimization problems that account for coverage effectiveness, resource consumption, and operational safety.

These enhancements will further improve the practical applicability and robustness of cooperative smoke-screen defense systems.

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