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An Optimization Model and Computational Framework for UAV Smoke Deployment Using Simulated Annealing and Genetic Algorithms

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Abstract: This paper addresses the issue of smoke screen formation for drone-deployed missiles by proposing a computational method integrating geometric modeling and intelligent optimization algorithms. Kinematic models for the drone, missile, smoke grenade, and smoke cloud are established within a three-dimensional coordinate system. By constructing a geometric occlusion criterion between the missile's line of sight and the spherical smoke cloud, the shielding process is transformed into a spatial intersection problem between a line and a sphere, enabling the calculation of effective shielding duration. Building upon this foundation, a nonlinear optimization model is established with maximum effective concealment duration as the objective function. This model incorporates variables such as flight direction, flight velocity, smoke grenade release time, and detonation time. For single-UAV deployment, parameter optimization is achieved using the simulated annealing algorithm. For multi-UAV coordinated deployment, a genetic algorithm is employed to ensure seamless coordination between multiple smoke screen coverage intervals. Simulation results demonstrate that this method effectively extends concealment duration while exhibiting excellent stability and adaptability.

Keywords: Simulated Annealing Algorithm, Genetic Algorithm, Cooperative Optimization.

1. Introduction

With the widespread application of unmanned systems in complex environments, employing smoke screens and other means to degrade the observational capabilities of incoming weapons has become an increasingly important research focus. Smoke screen concealment alters the line-of-sight conditions between the target and the observation platform, thereby reducing the likelihood of sustained tracking and identification. However, the actual effectiveness of smoke screens depends not only on their inherent properties but also on factors such as the flight trajectory of the deployment platform, release timing, and detonation sequencing. This results in a distinct spatiotemporal coupling characteristic during the concealment process. Existing research often relies on empirical rules or focuses on optimizing a single parameter. Under dynamic environments and multi-platform coordination conditions, it is challenging to simultaneously describe both the motion relationships and the geometric conditions of concealment, thereby limiting the capability for strategy optimization. Particularly in multi-UAV deployment scenarios, temporal overlap and spatial distribution among smoke clouds directly impact overall concealment duration, further evolving the problem into a high-dimensional nonlinear optimization process [1, 2].

To address these challenges, this paper establishes an algorithmic framework integrating geometric modeling with intelligent optimization algorithms. By establishing the motion relationships among UAVs, missiles, and smoke clouds, a geometric criterion based on line-of-sight obstruction conditions is constructed. This transforms the concealment process into a spatial relationship computation problem, upon which an optimization model targeting concealment duration is developed [3]. Simulated annealing and genetic algorithms are further introduced to perform optimization searches for both single-UAV and multi-UAV smoke deployment strategies, thereby enhancing overall concealment effectiveness [4].

2. Geometric Modeling of the Shielding Process

2.1. Modeling Approach

To evaluate the shielding effectiveness generated by smoke munitions deployed by a UAV, a geometric occlusion model is constructed. Under the specified operational scenario, the UAV flight direction, flight speed, smoke munition release time, and detonation delay are considered as known parameters. Based on these parameters, the time–position relationships of the UAV, missile, smoke munition, and smoke cloud center are established.

During the flight of the missile toward the decoy target, the missile observes the true target along a line of sight. Shielding occurs when this line of sight intersects the spherical smoke cloud generated by the munition detonation. Therefore, the shielding problem can be formulated as a geometric intersection problem between a line and a sphere.

By deriving the line-of-sight equation between the missile and the true target and comparing it with the spatial position of the smoke cloud, the time interval during which the line of sight is blocked can be determined. The effective shielding duration is obtained by calculating the time span in which the geometric occlusion condition is satisfied.

2.2. Kinematic Modeling

To describe the spatial relationships among all entities, a three-dimensional Cartesian coordinate system is established. The decoy target is defined as the coordinate origin, the xy plane represents the horizontal plane, and the z axis represents the vertical direction.

Within this coordinate system, the motion equations of the UAV, missile, smoke munition, and smoke cloud are formulated.

(1) UAV Motion Model

UAV FY1 moves toward the decoy target while maintaining a constant altitude. The decoy target position is defined as $P_{fake}(0,0,0)$, and the initial UAV position is $P_{FY1}(17800,0,1800)$.

The unit direction vector of the UAV flight is

$$n_{FY1} = \frac{(-17800,0,-1800)}{\sqrt{17800^2+0+1800^2}} \tag{1}$$

The UAV trajectory is expressed as

$$P_{FY1}(t) = P_{FY1} + v_{FY1}t, n_{FY1} \tag{2}$$

Where the UAV flight speed is $v_{FY1} = 120$ m/s.

(2) Missile Motion Model

Missile M1 moves toward the decoy target with a constant velocity of 300 m/s. The initial missile position is defined as $P_{M1}(20000,0,2000)$.

The unit direction vector of the missile motion is

$$n_{M1} = \frac{(-20000,0,-2000)}{\sqrt{20000^2+0+2000^2}} \tag{3}$$

The missile trajectory is given by

$$P_{M1}(t) = P_{M1} + v_{M1}t, n_{M1} \tag{4}$$

Where the missile speed is $v_{M1} = 300$ m/s.

(3) Smoke Munition Motion Model

After being released from the UAV, the smoke munition performs projectile motion under gravitational acceleration. The horizontal velocity remains equal to the UAV velocity, while the vertical motion follows free fall.

The downward unit vector is defined as $n_{-z} = (0,0,-1)$.

The trajectory of the smoke munition is expressed as

$$P_{decoy}(t) = P_{drop} + v_{FY1}(t - t_{drop}), n_{FY1} + \frac{1}{2}g(t - t_{drop})^2 n_{-z} \tag{5}$$

Where $P_{drop} = P_{FY1}(t_{drop})$ represents the release position.

(4) Smoke Cloud Motion Model

After a delay Δt, the smoke munition detonates and forms a spherical smoke cloud. The cloud center then descends vertically at a constant velocity of 3 m/s.

The trajectory of the smoke cloud center is given by

$$P_{cloud}(t) = P_{explode} + v_{cloud}(t - t_{explode})n_{-z} \tag{6}$$

Where $P_{explode} = P_{decoy}(t_{explode})$ and $t_{explode} = t_{drop} + \Delta t$.

2.3. Geometric Occlusion Criterion

The missile observes the true target along a line of sight. Shielding occurs when this line intersects the spherical smoke cloud. Consequently, the shielding problem can be transformed into determining the spatial relationship between a line and a sphere.

The shielding condition depends on the distance between the smoke cloud center and the missile–target line of sight.

Distance Criterion

Let the feature point on the true target be $P^e_{cru}(x_{p_e}, y_{p_e}, z_{p_e})$.

The vector from the feature point to the missile is

$$\overrightarrow{P_{M\iota}P^e_{cru}} = (x_{Mi} - x_{p_e}, y_{Mi} - y_{p_e}, z_{Mi} - z_{p_e}) \tag{7}$$

And the vector from the feature point to the smoke cloud center is

$$\overrightarrow{P_{cloud,k\iota}P^e_{cru}} = (x_{cloud,ki} - x_{p_e}, y_{cloud,ki} - y_{p_e}, z_{cloud,ki} - z_{p_e}) \tag{8}$$

The perpendicular distance between the smoke cloud center and the line of sight is

$$d_e = \frac{|\overrightarrow{P_{cloud,k\iota}P^e_{cru}} \times \overrightarrow{P_{M\iota}P^e_{cru}}|}{|\overrightarrow{P_{M\iota}P^e_{cru}}|} \tag{9}$$

When $d_e \le r$, the smoke cloud may intersect the line of sight.

Position Criterion

To generate effective shielding, the smoke cloud must lie between the missile and the target. The projection distance is defined as

$$d_{pro} = \frac{|\overrightarrow{P_{cloud,k\iota}P^e_{cru}} \cdot \overrightarrow{P_{M\iota}P^e_{cru}}|}{|\overrightarrow{P_{M\iota}P^e_{cru}}|} \tag{10}$$

The distance between the missile and the feature point is

$$d^e_{Mi} = \sqrt{(x_{Mi} - x_{p_e})^2 + (y_{Mi} - y_{p_e})^2 + (z_{Mi} - z_{p_e})^2} \tag{11}$$

Shielding occurs when $d_{pro} > d^e_{Mi}$.

2.4. Effective Shielding Duration

The smoke cloud remains effective for 20 s after detonation. The set of time points satisfying the occlusion condition is defined as

$$T_{total} = t_{explode} \le t \le t_{explode} + 20 \mid d_e(t) \le r,\ d_{pro}(t) > d^e_{Mi}(t) \tag{12}$$

Since shielding may occur intermittently, the earliest continuous sub-interval of T_{total} is defined as T_{eff}. The effective shielding duration is therefore expressed as $len(T_{eff})$.

2.5. Numerical Simulation

The model is solved through numerical simulation implemented in Python. The trajectories of the UAV, missile, smoke munition, and smoke cloud are computed using the derived kinematic equations. After detonation, the time domain is discretized and sampled to evaluate the occlusion condition.

The simulation yields the following key parameters:

Release position: $(17620.0,0,1800)$;

Detonation position: $(17188.0,0,1736.496)$;

Effective shielding duration: 1.4601 s.

3. Optimization Model for Single-UAV Smoke Deployment

3.1. Optimization Framework

Based on the geometric occlusion model established previously, the smoke deployment strategy for a single UAV carrying one smoke munition is further optimized. The objective is to maximize the effective shielding duration against a single incoming missile by adjusting the UAV flight direction, flight speed, munition release time, and detonation time.

The problem is formulated as a nonlinear constrained optimization model. The effective shielding duration is defined as the objective function, while the UAV kinematic constraints and the temporal constraints of smoke munition release and detonation define the feasible solution space. The geometric occlusion criterion derived in Section 5 is used to evaluate the shielding effectiveness of each candidate strategy.

3.2. Decision Variables

For the single-UAV single-munition scenario, the decision variables are defined as θ_{FY1}, v_{FY1}, t_{drop}, $t_{explode}$, where θ_{FY1} denotes the flight direction angle of UAV FY1, v_{FY1} denotes the UAV flight speed, t_{drop} denotes the smoke munition release time, and $t_{explode}$ denotes the detonation time.

These variables jointly determine the UAV trajectory, the munition release position, the smoke cloud detonation location, and the resulting shielding interval.

3.3. Kinematic and Occlusion Formulation

The missile trajectory is expressed as

$$P_{M_i}(t) = P_{M_i} + v_M t n_{M_i} \tag{13}$$

Where n_{M_i} is the unit direction vector from the initial missile position toward the decoy target.

The UAV trajectory is

$$P_{FY1}(t) = P_{FY1} + v_{FY1} t n_{FY1} \tag{14}$$

Where $n_{FY1} = (cos\,\theta_{FY1}, sin\,\theta_{FY1}, 0)$.

After release, the smoke munition follows projectile motion under gravity:

$$P_{decoy}(t) = P_{drop} + v_{FY1}(t - t_{drop})n_{FY1} + \frac{1}{2}g(t - t_{drop})^2 n_{-z} \tag{15}$$

Where $P_{drop} = P_{FY1}(t_{drop})$.

After detonation, the smoke cloud center moves downward at a constant velocity:

$$P_{cloud}(t) = P_{explode} + v_{cloud}(t - t_{explode})n_{-z} \tag{16}$$

Where $P_{explode} = P_{decoy}(t_{explode})$.

The shielding interval generated by the smoke cloud is defined as

$$T_{cloud} = t_{explode} \le t \le t_{explode} + 20 \mid d_e(t) \le r,\ d_{pro}(t) > d^e_{Mi}(t) \tag{17}$$

The effective shielding duration is obtained from the earliest continuous sub-interval of T_{cloud}:

$$max\ l\,en(T_{eff}) \tag{18}$$

3.4. Nonlinear Optimization Model

The optimization objective is defined as

$$max_{\theta_{FY1}, v_{FY1}, t_{drop}, t_{explode}} len(T_{eff}) \tag{19}$$

Speed constraint: $70 \le v_{FY1} \le 140$.

Direction constraint: $\theta_{FY1} \in (0, 360^{\circ})$.

Time constraints: $t_{drop} \ge 0$, $t_{explode} \ge 0$ and $t_{explode} \ge t_{drop}$.

Under these constraints, the optimization model searches for the parameter combination that maximizes the effective shielding duration.

3.5. Solution Method

The objective function is nonlinear and depends on time-varying geometric intersection relationships, making gradient-based optimization methods unsuitable. Therefore, a simulated annealing algorithm is adopted to perform global search within the feasible domain [5].

Simulated annealing is a stochastic optimization approach based on probabilistic acceptance of candidate solutions. During the early stage of the search, inferior solutions may be accepted with a certain probability, allowing the algorithm to escape local optima. As the temperature decreases, the search gradually focuses on high-quality regions of the solution space.

An initial feasible solution is randomly generated in the parameter space $(\theta_{FY1}, v_{FY1}, t_{drop}, t_{explode})$.

Small perturbations are introduced to produce neighboring solutions, and each candidate strategy is evaluated based on the resulting shielding duration. A cooling rate of 0.995 is used to gradually reduce the search range and improve local refinement near the optimum.

3.6. Optimization Results

The optimal strategy obtained by simulated annealing is summarized in Table 1.

Table 1. Optimal strategy for single-UAV smoke deployment

Item	Result
Maximum effective shielding duration	4.5900 s
Release time	0.10 s
Detonation time	0.79 s
UAV flight direction	7.06°
UAV flight speed	105.32 m/s

The optimized results show that the effective shielding duration can be significantly improved through the joint adjustment of UAV heading, flight speed, release timing, and detonation timing. The solution also indicates that the shielding performance is highly sensitive to the temporal coordination between munition deployment and smoke cloud formation. Therefore, precise control of both spatial trajectory and detonation timing is critical for achieving prolonged visual shielding.

4. Cooperative Optimization Model for Multi-UAV Smoke Deployment

A cooperative shielding strategy is developed for a multi-UAV deployment scenario in which three UAVs each carry one smoke munition. The objective is to maximize the longest continuous effective shielding interval against a single incoming missile.

Compared with the single-UAV case, the main challenge lies in coordinating the spatial trajectories and detonation timing of multiple smoke clouds so that their shielding intervals connect smoothly with minimal gaps or redundant overlap.

The missile detection moment is taken as the initial time. Based on the previously established kinematic model and geometric occlusion criterion, a nonlinear optimization model is constructed by jointly optimizing the flight direction, flight speed, release time, and detonation time of each UAV. The union of shielding intervals generated by the three smoke clouds is used to evaluate the overall shielding performance.

4.1. Multi-UAV Kinematic Representation

In the cooperative deployment scenario, UAV FY1, FY2, and FY3 each release one smoke munition. The motion model of each UAV remains identical to the single-UAV case, while the dimensionality of the decision variables increases.

The heading-angle vector and velocity vector are defined as

$$\theta_{FY} = \theta_{FY1}, \theta_{FY2}, \theta_{FY3};\ \ v_{FY} = v_{FY1}, v_{FY2}, v_{FY3} \tag{20}$$

Since each UAV deploys one smoke munition, the release-time vector and detonation-time vector are defined as

$$t_{drop} = t_{drop,11}, t_{drop,12}, t_{drop,13};\ t_{explode} = t_{explode,11}, t_{explode,12}, t_{explode,13} \tag{21}$$

The cooperative optimization model can therefore be represented as

$$M_{coop}: y = f(\theta_{FY}, v_{FY}, t_{drop}, t_{explode}) \tag{22}$$

Where y denotes the effective shielding performance generated by the cooperative deployment strategy.

4.2. Cooperative Optimization Model

The overall shielding effect is determined by the union of the shielding intervals generated by the three smoke clouds. For the j th smoke munition, the shielding interval is defined as

$$T_{cloud,j} = t_{explode,j} \le t \le t_{explode,j} + 20 \mid d_e(t) \le r,\ d_{pro}(t) > d_{Mi}^{e}(t) \tag{23}$$

The overall shielding interval is expressed as

$$T_{total} = \cup_{j=1}^{3} T_{cloud,j} \tag{24}$$

Because the shielding intervals may still be discontinuous, the optimization objective is defined as the length of the longest continuous shielding interval: $max\ l\ en(T_{eff})$, where T_{eff} denotes the longest continuous sub-interval extracted from T_{total}.

The decision variable set of the cooperative deployment problem is therefore

$$\theta_{FY1}, \theta_{FY2}, \theta_{FY3}, v_{FY1}, v_{FY2}, v_{FY3}, t_{drop,11}, t_{drop,12}, t_{drop,13}, t_{explode,11}, t_{explode,12}, t_{explode,13} \tag{25}$$

Which forms a 12-dimensional nonlinear optimization problem.

4.3. Constraints

The cooperative optimization model is subject to the same physical and temporal constraints as the single-UAV case, extended to all participating UAVs.

Speed constraint: $70 \le v_{FYk} \le 140, k \in 1,2,3$.

Direction constraint: $\theta_{FYk} \in (0,360^{\circ}), k \in 1,2,3$.

Release-time constraint: $t_{drop,1j} \ge 0, j \in 1,2,3$.

Detonation-time constraint: $t_{explode,1j} \ge 0, j \in 1,2,3$ and $t_{explode,1j} \ge t_{drop,1j}, j \in 1,2,3$.

Under these constraints, the model searches for the parameter combination that maximizes the continuous cooperative shielding duration.

4.4. Solution Method

Because the cooperative optimization problem is high-dimensional, nonlinear, and strongly coupled in both spatial and temporal domains, a genetic algorithm (GA) is adopted for global optimization [6].

The algorithm employs real-valued encoding to represent candidate strategies directly in the continuous parameter space. An initial population of feasible parameter sets is generated randomly, and each individual is evaluated according to its fitness value, defined as the effective shielding duration obtained from the cooperative deployment strategy.

Through iterative operations of selection, crossover, and mutation, high-quality individuals are preserved and gradually improved across generations.

In the implementation, 1000 candidate solutions are initialized and the evolutionary process runs for 1000 iterations. The optimization gradually converges toward the global optimum, yielding a maximum effective shielding duration of 9.4665 s.

4.5. Optimization Results

The optimized cooperative strategy is summarized in Table 2.

Table 2. Optimal cooperative strategy for multi-UAV smoke deployment

UAV	Flight direction	Flight speed	Release time	Fuse delay
FY1	12.58°	139.85 m/s	0.10 s	0.53 s
FY2	310.82°	100.9 m/s	2.53 s	0.12 s
FY3	165.60°	112.33 m/s	2.47 s	4.33 s

Maximum total effective shielding duration: 9.4665 s

4.6. Cooperative Strategy Analysis

As illustrated in Figure 1, the cooperative deployment strategy produces a clear time-complementary shielding pattern among the three UAVs. The smoke munition released by FY1 establishes the initial shielding interval of approximately 3.54 s. The smoke cloud deployed by FY2 subsequently extends the shielding interval by about 2.767 s and connects smoothly with the preceding interval, thereby avoiding a significant temporal gap.

The third UAV further prolongs the shielding duration, and the union of the three shielding intervals forms a continuous shielding period of approximately 9.47 s.

These results demonstrate that coordinated control of release timing and detonation timing among multiple UAVs can significantly improve shielding continuity compared with independent single-UAV deployment. The cooperative strategy effectively exploits temporal complementarity among smoke clouds and enhances the overall interference effectiveness.

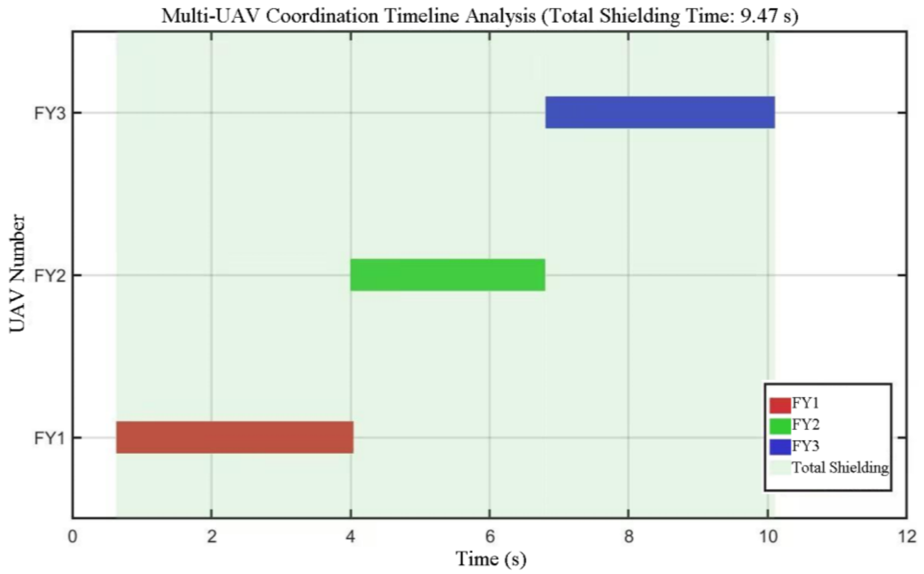

Figure 1. Multi-UAV coordination timeline analysis

5. Conclusion

This paper proposes an algorithmic model integrating geometric modeling and intelligent optimization for UAV-deployed smoke screens to improve the effectiveness of blocking the line of sight of incoming missiles. First, the three-dimensional motion relationships among the UAV, missile, smoke grenade, and smoke cloud are established, and a geometric criterion based on line-of-sight obstruction is constructed. The shielding process is transformed into spatial calculations between a line and a sphere, enabling quantitative evaluation of effective shielding duration under different deployment strategies. Second, a nonlinear optimization model is developed with shielding duration as the objective, integrating key parameters such as flight direction, speed, release time, and detonation time within a unified optimization framework. Third, simulated annealing and genetic algorithms are applied to solve single-UAV and multi-UAV deployment problems, improving global search capability. Simulation results show that the optimized shielding duration reaches 4.59 s for a single UAV and 9.47 s under multi-UAV cooperative deployment. Finally, the proposed model provides an effective approach for optimizing smoke screen deployment strategies. Future work may further consider more complex environmental conditions.

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