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UAV SMOKE-SCREEN OBSCURATION EVALUATION AND STRATEGY OPTIMIZATION VIA TIME-STEPPING SIMULATION AND SIMULATED ANNEALING

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Abstract: This paper develops a simulation-based framework for evaluating and optimizing UAV-deployed smoke-screen obscuration in missile engagement scenarios. First, the UAV, smoke cloud, missile, and protected target are described through a unified kinematic model, and angle and distance criteria are used to determine whether the smoke cloud effectively blocks the missile-target line. The valid time steps are accumulated to obtain the total effective obscuration duration, which provides a quantitative basis for strategy comparison. Second, the deployment problem is formulated as a constrained optimization task with UAV flight direction, flight speed, release time, and detonation delay as decision variables. A simulated annealing algorithm, combined with neighborhood search, exponential cooling, and bounded L-BFGS-B local refinement, is used to maximize the effective obscuration duration. Numerical results show that the baseline strategy provides 1.420 s of effective obscuration, while the optimized strategy increases it to 4.60 s, demonstrating the feasibility of the time-stepping simulation and optimization pipeline for smoke-screen deployment design.

Keywords: Smoke-screen obscuration; Time-stepping simulation; Simulated annealing; UAV deployment strategy; Constrained optimization

1 INTRODUCTION

Smoke-screen interference is a low-cost and flexible defensive method for reducing the probability that an incoming missile can continuously observe or lock on to a protected target. Instead of directly destroying the missile, a smoke-screen munition forms a cloud that blocks the missile-target line for a limited time. When the munition is carried by an unmanned aerial vehicle, the release position, detonation delay, flight direction, and flight speed can be adjusted before the cloud is generated. These parameters make the task suitable for mathematical modeling and algorithmic optimization, because the effective shielding duration depends on the coupled motion of the UAV, smoke cloud, missile, and target reference line.

The selected source sections raise two connected questions. The first question is how to evaluate whether a given smoke-screen deployment can produce valid obscuration and how long that valid period lasts. The second question is how to select flight and deployment parameters so that the valid obscuration time is as long as possible under physical and operational constraints[1-2]. Both questions require a quantitative model rather than a purely descriptive judgment. The source document therefore constructs a physical-rule-based time-stepping simulation. At each discrete instant, the positions of the missile and the smoke cloud are calculated, and angle and distance criteria are used to determine whether the cloud lies between the missile and the target and whether it is close enough to form an effective shield. An indicator function then accumulates all valid time intervals to obtain the total effective obscuration duration[3-5].

This paper follows that modeling route and reorganizes the selected content into an academic manuscript. The research scheme begins with the kinematic description of the UAV, smoke munition, missile, and smoke cloud, then establishes the geometric criteria and the effective-time summation formula. After the evaluation model is built, the decision variables are defined as the UAV flight direction, UAV speed, smoke release time, and detonation delay. The optimization objective is converted into a minimization form by taking the negative of the effective obscuration duration, and a simulated annealing algorithm is adopted for global exploration. The method further uses bounded local refinement to improve convergence within candidate regions[6]. The study also reports the numerical result of the first evaluation task and the optimized strategy of the second task, allowing the reader to connect formula construction, simulation procedure, parameter constraints, and convergence behavior in one consistent workflow. This organization highlights how a physical simulation can be embedded into an optimization loop for deployment planning and improves reproducibility for later verification. The translated and reformatted paper keeps the original technical logic, reported parameters, figures, and tables, while presenting the workflow as a compact study on simulation-based smoke-screen obscuration assessment and UAV deployment strategy optimization[7-8].

2 MODELING AND SOLVING

2.1 Establishment of the Smoke-Screen Obscuration Evaluation Model

2.1.1 UAV and smoke-munition trajectories

The direction vector of the UAV flying toward the decoy target is computed as:

$$\vec{D}_{\mathrm{drone}}=\frac{\vec{T}_{\mathrm{fake}}-\vec{p}_{d0}}{\|\vec{T}_{\mathrm{fake}}-\vec{p}_{d0}\|} \tag{1}$$

The velocity vector is:

$$\vec{V}_{d}=\vec{D}_{\mathrm{drone}} \tag{2}$$

2.1.2 Detonation point position

Given in the problem statement:

$$T_{\mathrm{drop}} = 3.6\mathrm{s},\ T_{\mathrm{delay}} = 1.5\mathrm{s} \tag{3}$$

The detonation point position can be written as:

$$P_{\mathrm{blast}}=(P_{\mathrm{drop}}+\vec{V}_{d}\times T_{\mathrm{delay}}-\frac{1}{2}\times g\times T_{\mathrm{delay}}\times T_{\mathrm{delay}}\times\vec{K}) \tag{4}$$

2.1.3 Missile position

The missile flies at a constant speed, where:

$$V_{m}=300\mathrm{m/s}$$

The missile direction vector and velocity vector are defined similarly:

$$\vec{D}_{\mathrm{missile}}=\frac{\vec{T}_{\mathrm{fake}}-\vec{p}_{m0}}{\|\vec{T}_{\mathrm{fake}}-\vec{p}_{m0}\|} \tag{5}$$

$$\vec{V}_{m}=\vec{D}_{\mathrm{missile}} \tag{6}$$

The missile position changes over time (x-axis only in the simplified setting):

$$\vec{p_{m}}=p_{m0}+V_{m}\times t \tag{7}$$

2.1.4 Smoke cloud evolution over time

The smoke cloud center position evolves as:

$$\vec{P}_{\mathrm{smoke}}=(x_{\mathrm{blast}},y_{\mathrm{blast}},z_{\mathrm{blast}}-V_{s}\times t) \tag{8}$$

2.1.5 Obscuration criteria and effective time

Angle criterion (whether the smoke is between the missile and the target):

$$\cos(\alpha)=\frac{\vec{MT}\cdot\vec{MS}}{\sqrt{\vec{MT}\cdot\vec{MT}}\times\sqrt{\vec{MS}\cdot\vec{MS}}}>0 \tag{9}$$

Distance criterion (whether the smoke is sufficiently close):

$$d=\frac{\|(\vec{p}_{s}-\vec{p}_{m})\times\vec{MT}\|}{\|\vec{MT}\|} \tag{10}$$

If $d<R(r=10)$, obscuration is formed.

Effective obscuration time is computed by summing valid time steps:

$$T_{E}=\sum_{T=0}^{T_{\max}}\Delta T\times I(T) \tag{11}$$

Here, $I(t)$ is an indicator function: it equals 1 when the angle criterion holds, the distance criterion holds, and the missile is inside the cloud; otherwise it equals 0.

2.2 Solving the Effective Obscuration Problem

The evaluation model mainly adopts a physical-rule-based time-stepping simulation algorithm. The core is to discretize the continuous timeline, compute the precise positions of the missile and the smoke at each time step, apply strict geometric and physical judgment criteria, and accumulate the effective time to obtain the total effective obscuration duration.

Table 1 clarifies the operational sequence of the evaluation model. It shows that effective obscuration is obtained through initialization, trajectory computation, dynamic time-step detection, and refinement, so the result is a cumulative simulation output rather than a single geometric judgment.

A three-dimensional visualization is generated (Figure 1) to show the effect of smoke interference on the missile.

By changing the time interval and discretization points, coarse and fine curves are obtained (Figure 2) to yield a more accurate result.

Final result analysis: after substituting the data and running the code, the obscuration duration is 1.420 s based on the curve and program outputs in Figure 2.

Table 1 Smoke-Screen Obscuration Evaluation Model

Step	Description
Step 1	Data initialization: set initial states and constants (Vm = 300 m/s, Tdrop = 3.6 s, Tdelay = 1.5 s, R = 10 m, Vs = 3 m/s).
Step 2	Trajectory computation: UAV releases the smoke munition at Tdrop; after Tdelay it detonates, forms a cloud, and then sinks at Vs; the missile flies at Vm toward the decoy target.
Step 3	Dynamic detection: from smoke detonation, at each small time step (t = 0.01 s) compute missile and smoke positions, apply the indicator function I(t), and accumulate effective time using the summation formula.
Step 4	Refinement: change time interval and discretization points to obtain coarse and fine curves for a more accurate result.

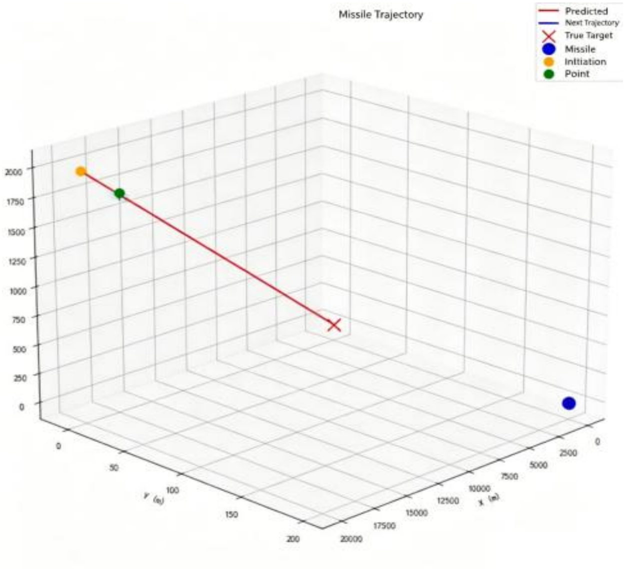

Figure 1 Smoke-Screen Interference Analysis

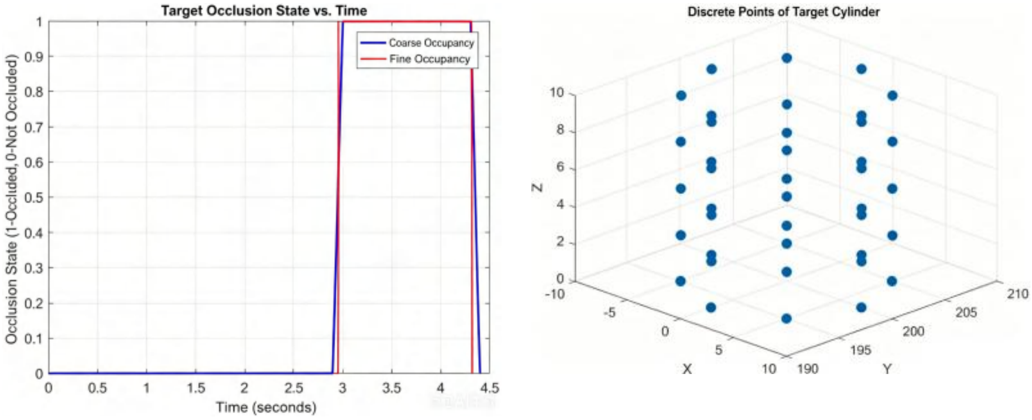

Figure 2 Coarse and Fine Search Results

2.3 Model Validation or Revision

Model reasonableness:

1) Assumption reasonableness: the model is built on a set of assumptions that simplify the problem and focus on key contradictions while remaining largely reasonable and realistic[9-10].

2) Logical correctness: the program strictly follows the mathematical and physical rules. The workflow from parameter computation to trajectory generation and stepwise obscuration judgment is clear, and the detailed outputs at key time points are consistent with the 3D visualization, supporting the correctness of the simulation.

3) Result reasonableness: the visualization shows a time interval where the missile trajectory intersects the sinking path of the smoke cloud, which visually supports the numerical result.

Model revision suggestions:

1) Introduce a more complex motion model: use a more complex guidance law (e.g., proportional navigation) to simulate missile maneuvers toward the target or interference source for higher realism.

2) Consider environmental factors: add wind speed and wind direction vectors to affect the smoke cloud drift path, extending the model to a windy environment.

3 MODELING AND SOLVING

3.1 Model Establishment

Table 2 Decision Variables and Constraints

Symbol	Meaning	Constraint
θ	UAV flight direction angle parameter	$\theta\in[0,2\pi]$
V_d	UAV flight speed	$V_d\in[70,140]$m/s
T_{drop}	Smoke release time	$T_{drop}\in[0,20]$s
T_{delay}	Detonation delay time	

Table 2 defines the four controllable decision variables used in the optimization model. These variables correspond to UAV direction, flight speed, release timing, and detonation delay, which means the mathematical search space is directly linked to deployable strategy parameters.

The objective function is defined as the negative of the effective obscuration time:

$$\min\int(\theta,V_d,T_{drop},T_{delay})=-calculate\_smoke\_obscuration(\theta,V_d,T_{drop},T_{delay}) \quad (12)$$

Here, calculate_smoke_obscuration is a simulation function that computes the effective obscuration time under a given parameter set.

Method selection: simulated annealing algorithm.

Table 3 Simulated Annealing Algorithm

Component	Description
State representation	Directly corresponds to the four decision variables (theta, Vd, Tdrop, Tdelay), forming a complete tactical plan.
Energy function	Transforms the maximization problem into a minimization problem to match the algorithm framework.
Step 1	Neighborhood search with random step sizes to explore the solution space and avoid local optima.
Step 2	Exponential cooling schedule that controls the acceptance probability of worse solutions: broad exploration early and fine search later.
Step 3	Local optimization using L-BFGS-B (with bounds) for fast local convergence within each basin.
Step 4	Termination with a fixed number of iterations (200) to balance computational cost and solution accuracy.

Table 3 explains how the simulated annealing procedure is organized. The state vector represents a complete tactical plan, the energy function converts duration maximization into minimization, and the cooling and local-refinement steps balance global exploration with local convergence.

3.2 Model Solution and Analysis

Parameter settings and initialization:

1) Initial solution: $\theta=0$, $V_d=140$m/s, $T_{drop}=1.5$s, $T_{delay}=3.6$s.

2) Iterations: 200 main iterations.

3) Local refinement: L-BFGS-B with a maximum of 100 iterations.

Optimization process analysis (Figure 3):

1) Convergence characteristics: the curve improves rapidly early and then gradually converges, consistent with typical simulated annealing behavior.

2) Parameter evolution: the four parameters are continuously adjusted within their bounds and finally stabilize near the optimal values.

3) Search diversity: parameter changes indicate that the algorithm performs sufficient global exploration.

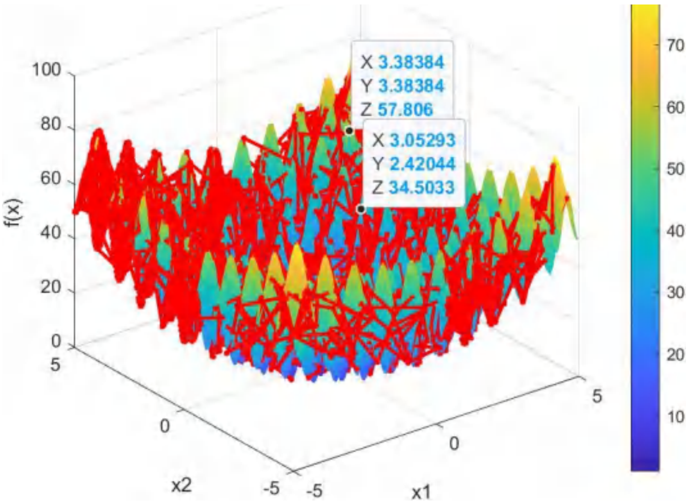

Figure 3 Simulated Annealing Model Demonstration

A visualization process is provided (Figure 4) to better illustrate the optimization process and outcomes.

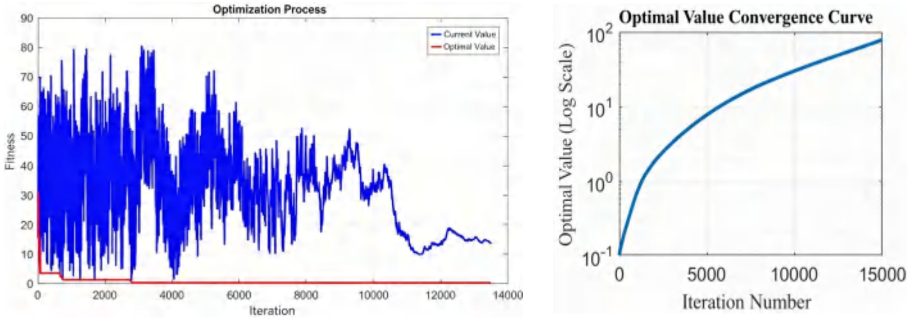

Figure 4 Simulated Annealing Optimization Visualization

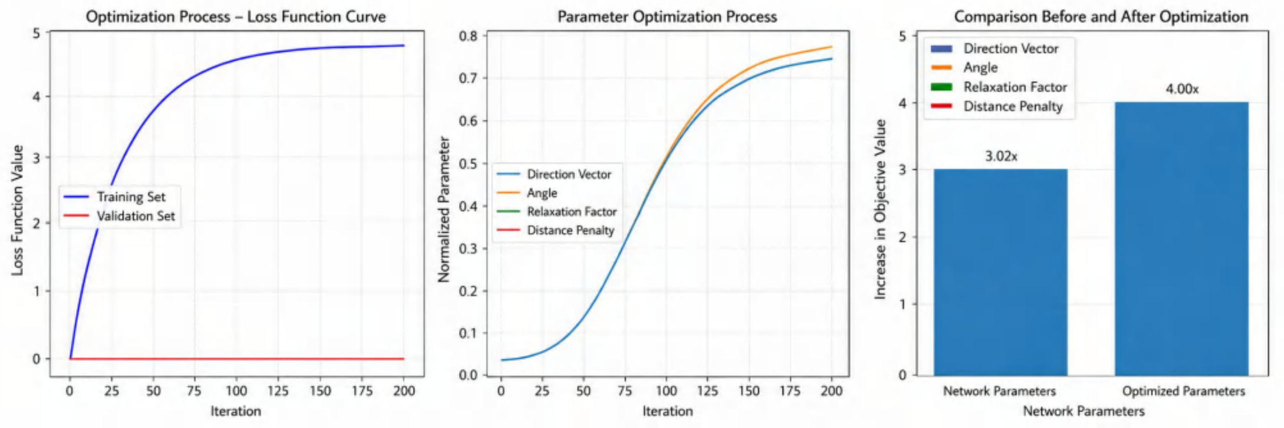

Figure 5 Optimization Curve and Before-After Comparison

Figure 5 shows the optimization curve and the comparison before and after optimization.
Final optimization results are summarized as follows:

Table 4 Optimal Decision Result

Parameter	Optimal strategy result
UAV flight direction angle parameter theta	31.2402 rad (about 1789.93 degrees)
UAV flight speed Vd	121.32 m/s
Smoke release time Tdrop	Release at 3.72 s after mission start
Detonation delay time Tdelay	Detonate at 34.82 s after release
Expected effective obscuration time	4.60 s

Table 4 reports the optimized strategy and its expected effect. Compared with the baseline effective obscuration time of 1.420 s, the optimized parameter combination increases the duration to 4.60 s, showing that release timing and detonation delay have substantial influence on the shielding window.

3.3 Model Validation or Revision

Model reasonableness:
1) Physical reasonableness: the parameters of the optimal solution are within physically achievable ranges.
2) Convergence verification: multiple independent runs converge to similar results, indicating stability (Figure 6).
Possible sources of error:
1) Simulation model error caused by simplified assumptions in the calculate smoke obscuration function.
2) Discretization error introduced by the time-stepping discretization.
Model revision suggestions:
1) Introduce an adaptive step size to dynamically adjust the neighborhood search range.
2) Use a hybrid optimization strategy by combining genetic algorithms and other global search methods to avoid local optima.
3) Multi-start optimization: search from multiple initial points to check the consistency of results.

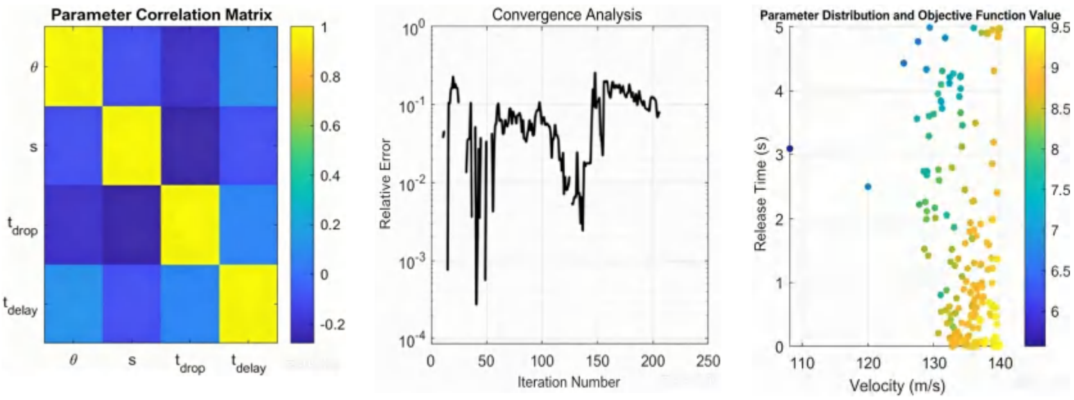

Figure 6 Convergence and Reasonableness Analysis

4 CONCLUSION

This paper constructs a time-stepping simulation and optimization framework for UAV-deployed smoke-screen obscuration. The evaluation module couples the motion of the UAV, smoke cloud, missile, and target line, and uses angle and distance criteria to accumulate effective obscuration time. The baseline calculation obtains 1.420 s of valid obscuration, confirming that the geometric judgment procedure can quantify whether a given smoke release scheme is effective. On this basis, the strategy optimization module treats UAV direction, speed, release time, and detonation delay as bounded decision variables. Simulated annealing with local L-BFGS-B refinement extends the effective obscuration duration to 4.60 s, which indicates that the proposed simulation-optimization pipeline is useful for comparing and improving deployment schemes.

Future research should further enhance model realism in three aspects. First, the missile trajectory can be described by proportional navigation or other guidance laws instead of simplified straight motion. Second, wind field, atmospheric diffusion, smoke concentration decay, and cloud deformation should be incorporated to describe the time-varying shielding ability of the smoke cloud. Third, multi-UAV cooperative deployment and hybrid global-local optimization algorithms can be studied to improve robustness under uncertain battlefield conditions. These extensions would make the model more suitable for complex dynamic scenarios and support more reliable smoke-screen deployment decision-making.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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