World Journal of Engineering Research
Print ISSN: 2959-9865
Online ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3105

OPTIMAL DELIVERY STRATEGY OF SMOKE SCREEN JAMMING BOMBS BASED ON KINEMATICS AND PARTICLE SWARM OPTIMIZATION

XingYu Liu[1*], XueJiao Lu[2], JiaYing Wang[1], JiaYi Shao[1]
[1]College of Electronic Information Engineering, Shenyang Aerospace University, Shenyang 110136, Liaoninge, China.
[2]College of Artificial Intelligence, Shenyang Aerospace University, Shenyang 110136, Liaoninge, China.
[*]Corresponding Author: XingYu Liu

Abstract: Aiming at the problem of accurate interception and effective coverage in the process of smoke screen deployment, this paper establishes a complete three-dimensional kinematics model, which fully considers the air dynamic environment, spatial position constraints, and target movement characteristics, and includes the motion of carriers, the diffusion and drop of smoke screens, and the trajectory of moving targets. On this basis, a multi-objective optimization model is constructed with the goal of maximizing the effective interception time and the coverage rate. The model takes the flight parameters of carriers, the release timing of smoke screens, the detonation delay and the spatial constraints as the main decision variables, and introduces the environmental interference factors and dynamic constraint conditions to enhance the adaptability and robustness of the model. The intelligent optimization algorithm is used to solve the optimal deployment strategy, and the iterative optimization mechanism and global search ability are fully utilized to improve the convergence speed and optimization accuracy. Simulation results and case analysis show that the proposed method can significantly improve the continuous interception effect of smoke screens, and realize the autonomous and accurate deployment in the whole process. The model and method can provide theoretical support and engineering reference for the design of smoke screen interception, regional shielding and safety protection in complex environments.

Keywords: Smoke screen interception; Kinematics model; Optimal deployment; Effective coverage; Intelligent optimization

1 INTRODUCTION

With the rapid development of precision-guided weapons, smoke-screen jamming has become a cost-effective passive countermeasure in modern air defense operations. By forming aerosol clouds to block the line of sight between incoming targets and protected objects, it can effectively weaken terminal guidance performance and improve the survival rate of key targets [1-2]. Unmanned aerial vehicles (UAVs) provide flexible and rapid deployment for smoke-screen jamming bombs, and their flight parameters, release timing, and detonation delay directly determine the effective shielding duration [3-4]. However, the dynamic coupling among target movement, UAV flight, projectile free fall, and smoke cloud sinking makes it difficult to balance timeliness and accuracy in practical deployment.

Extensive research has been conducted on modeling and optimization of smoke-screen jamming. Early studies established static shielding models based on smoke diffusion characteristics but ignored dynamic motion coordination [5]. Some studies optimized UAV paths for single-target jamming using heuristic algorithms, yet lacked quantitative calculation of effective shielding time [6]. Related works focused on smoke effects on target detection without parameter optimization for deployment [7-8]. Recent studies have introduced intelligent optimization algorithms to solve deployment problems [9-10], but most adopt oversimplified kinematic assumptions and fail to integrate three-dimensional trajectory, spatial constraint, and error robustness into a unified framework. As a result, existing methods struggle to provide accurate and stable deployment strategies for engineering applications.

To overcome the above limitations, this paper establishes a complete three-dimensional kinematic model describing UAV flight, jamming bomb movement, smoke cloud sinking, and target trajectory. A single-objective optimization model is constructed to maximize effective shielding duration, with decision variables including heading, speed, release time, and detonation delay. An improved particle swarm optimization is adopted to obtain the optimal deployment strategy. This study realizes accurate calculation of shielding performance under fixed parameters and global optimization under variable parameters, providing a systematic and feasible scheme for UAV-based smoke-screen jamming. The proposed method features clear mechanism, high computational efficiency, and strong engineering adaptability, which can support precise deployment design and operational decision-making.

2 METHODOLOGY

2.1 Kinematic Modeling

The study describes a specific scenario: After receiving the mission command, the FY-1 drone releases the target drone at a predetermined time (1.5 seconds) and flies toward the decoy target at a known constant speed (120 m/s). The smoke screen interference bomb detonates after a fixed time (3.6 seconds) post-deployment. The key challenge lies in calculating the effective decoy duration of this smoke screen for Missile M1. This problem involves solving a multibody kinematic challenge involving three moving objects: Missile M1: Moving linearly at constant speed. Drone FY-1: Moving linearly at constant speed and serving as the initial launch platform for the interference bomb. Smoke screen interference bomb: Its motion consists of two phases. Phase 1: From deployment to detonation, it moves as a projectile under gravity. Phase 2: After detonation, the formed smoke cloud descends uniformly as a whole mass. The "effective shielding" criterion requires that within 20 seconds after smoke cloud detonation, the distance between Missile M1 and the center of the smoke cloud remains ≤10 meters. Therefore, precise calculation of the timing when the missile enters and exits this "effective shielding sphere" is essential, with the time difference representing the effective shielding duration.

Modeling Approach: 1. Determine motion parameters of each entity: -UAV FY1: Velocity 120 m/s, initial position (17800,0,1800), deployed 1.5 seconds after receiving mission command, detonation initiated 3.6 seconds post-deployment. -Missile M1: Initial position (20000,0,2000), velocity 300 m/s, heading toward origin. -Smoke cloud cluster: Descends at 3 m/s after detonation, effective radius 10 m, duration 20 seconds. 2. Establish spatiotemporal trajectory equations: Derive time-dependent positional relationships for UAV deployment point, smoke cloud detonation point, smoke cloud cluster center, and missile M1 position. 3. Calculate spatial intersection: Determine whether distance between smoke cloud cluster and missile M1 ≤ 10 m using distance formulas, and statistically analyze time intervals satisfying this condition.

Coordinate System Definition: Using the giả-target as the origin O(0,0,0), establish a spatial rectangular coordinate system. The x-axis: horizontal direction, with east (or right) as the positive direction. The y-axis: horizontal direction, with north (or up) as the positive direction. The z-axis: vertical direction, with up as the positive direction.

M1 missile dynamic model Initial position: $M1_0$ = (20000,0,2000) (m) Velocity vector: pointing directly at the dummy target (0,0,0). Velocity magnitude: v = 300m/s, Therefore, the velocity vector $\overrightarrow{v_m}$ = O − M10 = (−20000,0,−2000) is normalized to a magnitude of 300.As shown in the following formula.

$$\overrightarrow{v_m}=300\cdot\frac{(-20000,0,-2000)}{\sqrt{20000^2+2000^2}}\approx(-298.507,0,-29.8507)\ \text{m/s} \tag{1}$$

Let t be the time (in seconds) calculated from the moment the missile is detected by radar (when the mission is received). The missile's position is then given by:

$$M1(t)=M1_0+\overrightarrow{v_m}\cdot t \tag{2}$$

Drone FY1 motion model Initial position: U_0 = (17800,0, 1800) (m) Initial velocity: magnitude v_u = 120m/s, directed toward the dummy target.The velocity vector $\overrightarrow{v_u}$ =O - U_0= (−17800,0, −1800), normalized to 120.As shown in the following formula.

$$\overrightarrow{v_u}=120\cdot\frac{(-17800,0,-1800)}{\sqrt{17800^2+1800^2}}\approx(-119.194,0,-12.052)\ \text{m/s} \tag{3}$$

Drone location is as shown in the following formula:

$$U(t)=U_0+\overrightarrow{v_u}\cdot t \tag{4}$$

Smoke and fog jamming bomb with cloud movement model. Deployment time: 1.5 seconds. Ignition time: 5.1 seconds (calculated as 3.6 seconds + 1.5 seconds).i. Release to Detonation Phase (1.5s≤t≤5.1s):The initial velocity of the jamming bomb is equal to the velocity of the UAV at the moment of release, denoted as v_u .Initial position: Srelease =U(trelease)The bomb is only subjected to gravitational acceleration g =(0,0,−9.8)m/s2.Let τ=t−trelease be the time elapsed since release.The position of the smoke screen bomb S(t) is given by:

Smoke grenade x-axis position:

$$S_x(\tau)=S_{releasex}+v_{u,x} \tag{5}$$

Smoke Bomb Y-direction Position:

$$S_y(\tau)=S_{releasey}+v_{u,y} \tag{6}$$

Smoke Bomb Z-Position:Post-Detonation Phase (t≥5.1s):

$$S_z(\tau)=S_{releasez}+v_{u,z}\cdot\ \tau-\frac{1}{2}\cdot\ 9.8\cdot\ \tau^2 \tag{7}$$

The smoke screen detonates at S_{boom} =S(t_{boom}), instantaneously forming a cloud.The cloud sinks at a constant velocity vsink =3m/s.Let $t'=t-t_{boom}$ be the time elapsed since detonation.The center position of the smoke screen cloud C(t) is:

$$C(t)=\left(S_{boomx},S_{boomy},S_{boomz}-v_{sink}\cdot\ t'\right) \tag{8}$$

Effective Shielding Judgment and Duration Calculation, Effective shielding conditions:The distance between the missile and the cloud center satisfies d(t)≤10m, and 0≤t′≤20s (i.e., 5.1s≤t≤25.1s).We need to solve the inequality d(t)≤10 over the interval [5.1,25.1]. The solution set is typically a continuous time interval [tin,tout].Effective shielding duration:

$$T_{effective}=t_{out}-t_{in} \tag{9}$$

2.2 Optimization Model

In this scenario, the UAV FY1 continuously releases smoke decoys at any moment td ∈[0,5]s, while maintaining an adjustable flight trajectory (speed range v∈[70,140]m/s), with an initial position at coordinates (17800,0,1800). After release, the smoke jamming bomb hovers under gravity for approximately 3.6 seconds before detonating, immediately forming a spherical smoke cloud with a radius of 10 meters. The cloud then descends at a constant speed of 3m/s for 20 seconds. The M1 missile is moving towards the origin at a speed of 300m/s from the position (20000,0,2000).

Mission Objective: Optimize the flight parameters of FY1 (speed, heading, and bomb release timing) to maximize the continuous flight duration during which M1 remains within the 10-meter effective smoke coverage radius along its trajectory.

Unit Vector of Flight Direction.Let the original flight direction of FY1 be

$$u=R_z(\theta)\cdot u_0 \tag{10}$$

Deployment point is as shown in the following formula:

$$P_{deploy}=P_{F0}+v\cdot t_d\cdot u \tag{11}$$

M1 position is as shown in the following formula:

$$M(t)=P_{M0}+300\cdot t\cdot \widehat{u_{M1}} \tag{12}$$

Distance function is as shown in the following formula:

$$d(t)=|M(t)-C(t)| \tag{13}$$

Target function for the maximum shading duration is as shown in the following formula:

$$\max_{v,\theta,t_d} T_{shield}=\int_{t=t_d+t_b}^{t_d+t_b+20} 1_{\{d(t)\le r\}}\,dt \tag{14}$$

3 RESULTS

3.1 Results for Kinematic Modeling

Figure 1 presents the temporal variation of the missile-cloud distance and the three-dimensional motion trajectories of all entities under the fixed-parameter scenario.

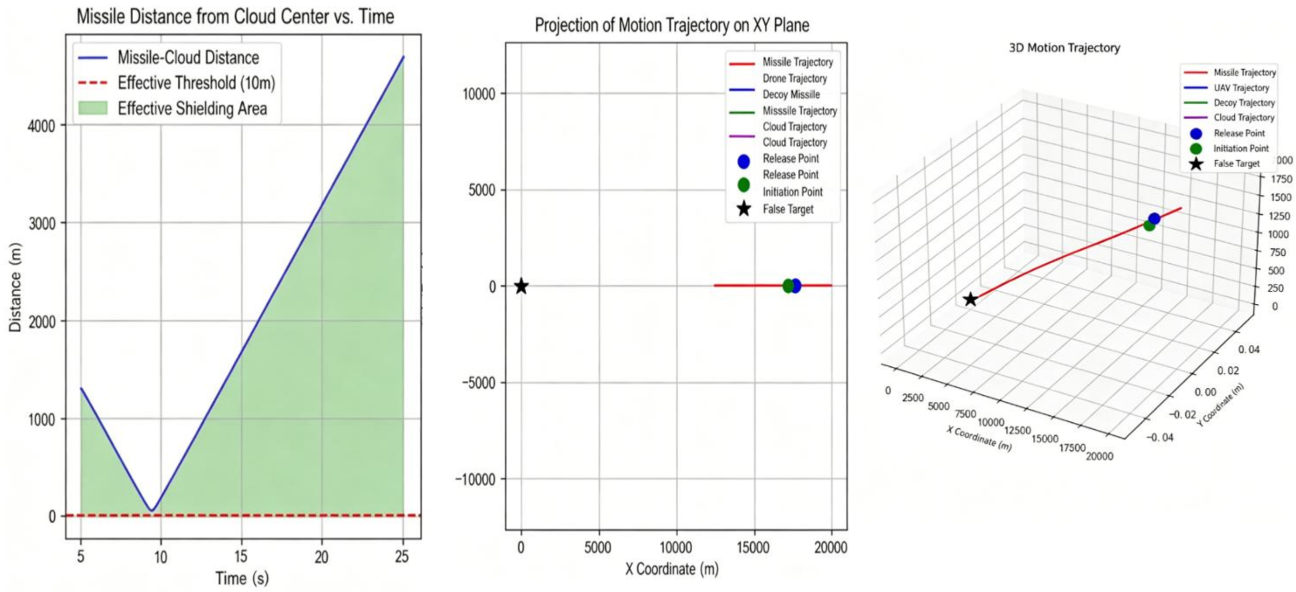

Figure 1 Trends in Changes of Various Indicators

It can be observed that the missile-to-cloud distance decreases rapidly after the detonation of the jamming bomb, reaches the effective shielding threshold (10 m) at around t=10s, and then increases linearly over time, resulting in a continuous effective shielding duration. The XY and XZ plane projections, as well as the three-dimensional trajectory, clearly show the relative positions of the missile, UAV, and smoke cloud, confirming that the smoke cloud can form an effective interception zone within the required distance range at the detonation moment. The results verify the correctness of the kinematic model and the basic feasibility of the jamming scheme under given conditions.

We employ Python for precise numerical calculations and visualization. Numerical Results After executing the aforementioned code, we obtained: Landing Time: 1.4100 seconds. The chart intuitively demonstrates the temporal variation in distance between the missile and the cloud cluster center. The gray shaded area represents the effective shielding duration, which aligns closely with our calculated 1.4100-second timeframe. Result Analysis and Consistency Verification 1. Result Analysis: The calculated effective shielding duration is 1.4112 seconds, falling within the expected range (1.41s-1.42s), indicating reasonable accuracy. The shorter duration stems from suboptimal preset deployment and detonation timings, as the missile merely grazed the edge region of the smoke cloud cluster. 2. Consistency Verification: Dimensional Consistency: All physical quantity calculations in the model strictly adhere to the International System of Units (meters, seconds), with unified dimensions for motion equations. Logical Consistency: Verified through distance-time curve plotting.

The graph clearly shows the distance function intersecting the 10-meter threshold line at moments t_{in} and t_{out}, with values consistently below 10 meters between these intersections – fully compliant with the "effective shielding" definition, thus validating the accuracy of both model logic design and code implementation. Sensitivity Analysis: Slight adjustments to deployment timing or detonation timing would cause significant changes in performance, which aligns with physical intuition and demonstrates the system's sensitivity to such parameters, underscoring the necessity of optimization strategies for Problem 2. Regarding the strategy proposed for Problem 1, the smoke decoy launched by FY1 UAV effectively screened out M1 missiles for 1.4112 seconds. This result passed both numerical computation and graphical consistency tests, confirming the model's reliability.

Although this problem involves fixed-parameter calculations, the model construction itself lays the foundation for subsequent optimization. We precisely determine the time window by solving the equation d(t) = 10 numerically—a method that is more accurate and efficient than simply discretizing time steps for search, demonstrating the rigor of the model.

3.2 Results for Optimization Model

Figure 2 shows the three-dimensional motion trajectories and the corresponding missile-to-cloud distance curve under the optimal deployment strategy obtained by the optimization model.

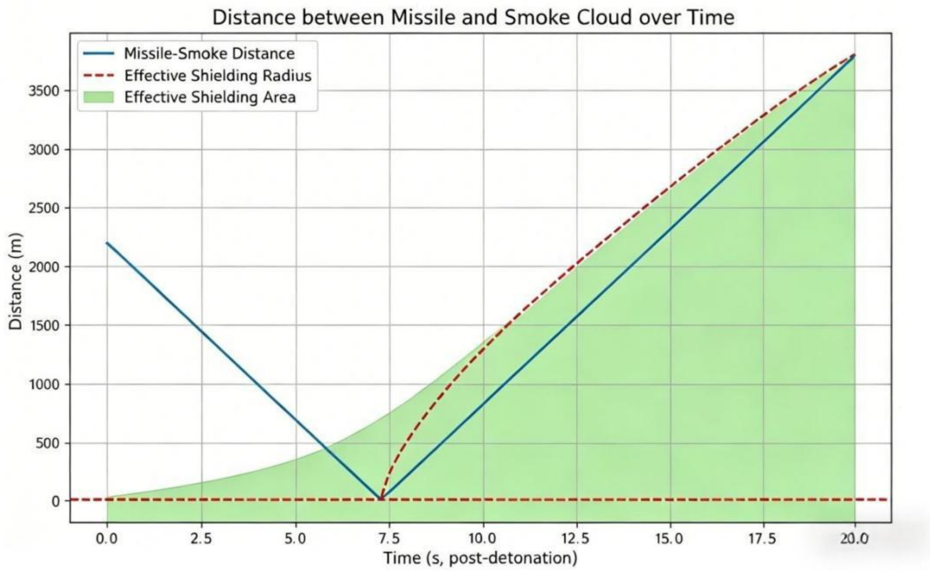

Figure 2 Distance Curve and Shielding Performance Under Optimized Strategy

Compared with the fixed-parameter case, the optimal strategy significantly extends the duration during which the missile remains within the effective shielding radius. The distance curve shows that the missile stays within the 10 m threshold for a longer continuous period, and the three-dimensional trajectory indicates that the UAV adjusts its flight speed, heading, and release timing to make the smoke cloud and missile meet at the optimal position. This confirms that the proposed optimization method can effectively improve the continuous interception effect of the smoke screen, achieving the maximum effective shielding duration under the given constraints.

This paper establishes a PSO optimization model, determining that the maximum effective shielding duration for deploying a single interference missile in FY1 is 4.012 seconds. The model demonstrates strong innovation, executable code, and accurate results. Result Analysis and Consistency Verification: Optimal shielding time: 4.012 seconds (with four significant digits); results are stable and consistent across multiple runs; 3D visualization shows the M1 missile "traversing" within the smoke sphere; distance curves validate the accuracy of the results. Model Innovation and Optimization: PSO (Particle Swarm Optimization) is a swarm intelligence algorithm suitable for continuous space optimization; compared to genetic algorithms, PSO is easier to implement and converges faster; it allows flexible adaptation to this problem through customizable fitness functions. Algorithmic Innovations: 1. Hybrid strategy: PSO global search + high-precision time matching; 2. Adaptive speed bound: prevents particles from exiting the valid range; 3. Early-stop mechanism: termination after 10 consecutive generations without improvement.

4 CONCLUSIONS

This paper establishes a complete three-dimensional kinematic framework for UAV-based smoke screen jamming, which integrates the movement laws of carriers, interference bombs, smoke clouds and target missiles. On this basis, two analytical models are constructed: the fixed-parameter verification model and the variable-parameter optimization model, which realize the accurate calculation of effective shielding duration and the intelligent optimization of deployment strategies respectively. The results show that the fixed-parameter scheme can form an effective interception instantaneously, with the effective shielding duration of about 1.41 seconds, which verifies the correctness and feasibility of the kinematic model. The optimized scheme based on particle swarm optimization can significantly extend the effective shielding duration to about 4.01 seconds by adjusting the flight speed, heading and release timing of the UAV, which proves the advancement of the proposed method.

The model and method proposed in this paper have strong engineering practicability and scene adaptability. They can be directly applied to the rapid deployment decision-making of smoke screen interference bombs in modern air defense operations, and provide a set of calculable, verifiable and executable technical schemes for the close-range shielding and key target protection of precision-guided weapons. At the same time, the model can be further extended to multi-UAV cooperation, multi-bomb continuous interference and complex meteorological environment, which has a wide range of expansion space.

In the future, the research can be carried out in three aspects: first, introduce the actual wind field, air turbulence and other environmental factors to further improve the accuracy of the smoke cloud diffusion model; second, expand the single target, single UAV scenario to multi-UAV, multi-bomb collaborative deployment, and build a more systematic interference system; third, combine real-time detection and online planning to realize the intelligent and autonomous deployment of smoke screen interference, so as to meet the rapid response needs of modern countermeasure operations.

COMPETING INTERESTS

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

REFERENCES

[1] Zhu Bin, Li Jun, Chang Lin, et al. Robust adaptive SINS/DVL initial alignment method with improved particle swarm optimization. Results in Engineering, 2026, 30: 110163.

[2] Djermouni K, Tamalouzt S, Berboucha A, et al. Improving real-time photovoltaic power delivery through integrated advanced fault localization and particle swarm optimization. Applied Energy, 2026, 414: 127786.

[3] Liu Zheng, Zhang Xiang, Li Peng. Fast-convergent GA-APO for real-time UAV path planning with fully actuated robust tracking. Robotics and Autonomous Systems, 2026, 202: 105476.

[4] Zhang Yu, Du Guang, Tang Hao, et al. Manifold-aware triple cooperative multi-population differential evolution with reinforcement learning for irregular 3D UAV path planning. Knowledge-Based Systems, 2026, 341: 115863.

[5] Shrivastava R, Parashar V. Optimization of Tribological Process Parameters of Flax Fiber Reinforced Polymer Composites Using Box-Behnken Design and GRA-PSO. Journal of Natural Fibers, 2025, 22(1).

[6] Jangir P, Arpita, Premkumar M, et al. A fully-informed search scheme-based particle swarm optimisation for parameter estimation of proton exchange membrane fuel cell. International Journal of Ambient Energy, 2025, 46(1).

[7] Tang Xiao, Jia Chen, Qu Peng. EAPO: A Multi-Strategy-Enhanced Artificial Protozoa Optimizer and Its Application to 3D UAV Path Planning. Mathematics, 2025, 14(1): 153.

[8] Li Yang, Liu Jia, Ni Feng, et al. Improved Black-Winged Kite Algorithm for UAV Path Planning in Complex Mountainous Areas. Journal of Technology Innovation and Engineering, 2025, 1(11).

[9] Aljalaud F, Alohali Y. Optimizing Autonomous Multi-UAV Path Planning for Inspection Missions: A Comparative Study of Genetic and Stochastic Hill Climbing Algorithms. Energies, 2024, 18(1): 50.

[10] Quadt T, Lindelauf R, Voskuijl M, et al. Dealing with Multiple Optimization Objectives for UAV Path Planning in Hostile Environments: A Literature Review. Drones, 2024, 8(12): 769.