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Delivery Strategy and Optimization Model of Smoke Screen Jamming Projectiles Based on Geometric Model

Jianchao Yu[1], Jinkun Chen[1], Yating Zhong[2], Guorui Zhao[3,*]

[1]School of Mechanical and Energy Engineering, Guangdong Ocean University, Yangjiang, 529500, China
[2]School of Business, Guangdong Ocean University, Yangjiang, 529500, China
[3]School of Computer Science and Technology, Guangdong Ocean University, Yangjiang, 529500, China
[*]Correspondence: zhaoguoruimath@foxmail.com

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Abstract: The integration of smoke screen jamming projectiles with new materials and intelligent control technologies provides critical protection support for modern and future battlefields. Aiming at the timing constraints of coordinated delivery by multiple UAVs and the solution space explosion problem in multi-target jamming, this paper constructs a mechanism model based on spatial geometry and the standard quadratic form of elliptic equations. Combined with the line-of-sight (LOS) guidance law, a nonlinear three-dimensional relative motion model is established. The simulated annealing algorithm is improved through greedy strategy initialization, an inferior solution penalty mechanism and a neighborhood generation strategy, which significantly enhances the solution efficiency in complex scenarios. For the multi-UAV, multi-projectile and multi-objective optimization problem, the results show that compared with the effective shielding duration of 1.391 seconds obtained by using only the spatial geometric model, the dynamic shielding model optimized by the improved algorithm extends the effective shielding duration to 22.97 seconds. Comparative experiments demonstrate that the improved algorithm outperforms traditional heuristic algorithms in terms of convergence speed and solution optimality. The combination of spatial geometric modeling and heuristic algorithms can effectively improve the battlefield protection effectiveness of smoke screen jamming projectiles.

1. Introduction

The operational form of modern local warfare is undergoing fundamental transformation with the development of unmanned systems and precision guidance technology. As shown in the Russia-Ukraine conflict (precision-guided weapons) and U.S.-Iran conflicts (UAV swarms), traditional single-point protection systems cannot cope with multi-dimensional, multi-batch precision strike threats. In recent U.S.-Iran confrontations, Iran’s Shahed-136 UAV swarms (low-cost, cooperative) and the U.S.’s new autonomous Lucas UAVs have proven that multi-UAV cooperative combat is the core of modern battlefield systems. Smoke jamming projectiles, verified by Shen et al.[1], effectively attenuate guidance signals and reduce hit probability; integrated with UAVs, they block guided weapon tracking and have high practical value.

The core requirements of multi-UAV cooperative smoke delivery are accurate timing matching, maximized multi-target jamming efficiency, and global optimization of delivery strategies. Olfati-Saber (2007)[2] established the multi-agent network consensus theory, laying the foundation for UAV distributed cooperative control. RW (2008)[3] improved distributed consensus algorithms for path planning and timing scheduling. In terms of guidance and motion modeling, Zarchan[4](in Tactical and Strategic Missile Guidance) elaborated the LOS guidance law; Shneydor[5] derived missile guidance dynamics, providing support for 3D motion modeling; Beard and McLain[6] extended the LOS guidance law to UAV control, enabling precise trajectory modeling. Kirkpatrick et al. (1983)[7] proposed the simulated annealing algorithm, suitable for large-space, highly constrained optimization such as smoke jamming strategy design[8].

However, existing research has obvious limitations: most focus on single-platform optimization, static smoke modeling, and single-target evaluation. Simplified 2D models fail to capture 3D dynamic interactions and cooperative timing[9.10,11], leading to poor generalization. Traditional algorithms suffer from slow convergence and insufficient optimality, failing to meet real-time decision-making needs[12,13].

To address these issues, this paper studies multi-UAV cooperative smoke jamming optimization, integrating multi-agent cooperation, LOS guidance, and simulated annealing. A complete model system is constructed, including geometric shielding models (spatial geometry, elliptic equations) and 3D nonlinear relative motion models (LOS guidance). Single-objective and multi-objective optimization models (with timing/cloud interaction constraints) are established. An improved simulated annealing framework (greedy initialization, inferior solution penalty, neighborhood generation) is proposed. Case simulations and comparative experiments verify the model’s rationality and the algorithm’s superiority, providing theoretical and technical support for practical applications.

The proposed model and technology have significant promotion value, applicable to air-to-ground missile guidance and UAV trajectory planning. To solve UAV motion limitations, PID control (based on LOS guidance)[14] is introduced to build a closed-loop system for flexible speed/direction adjustment and dynamic tracking. In the future, parameters and algorithms will be optimized to promote engineering implementation and improve equipment motion control performance.

2 Model Construction

2.1 Basic Assumptions

UAVs maintain uniform linear motion at a constant altitude with fixed heading and velocity after mission initiation, ignoring attitude changes and airflow disturbances. Smoke projectiles are only affected by gravity after release, form spherical clouds instantly upon detonation, and sink at a constant speed while keeping spherical shape, without considering concentration attenuation and wind field. Air-to-ground missiles fly along a fixed trajectory at constant velocity toward the decoy target, ignoring maneuvering and detection errors. Each UAV operates independently without flight conflicts; mission assignment and command transmission delays are neglected.

2.2 Geometric Shielding Judgment Model

The dynamic-based geometric shielding judgment model takes the shielding time of the missile by the spherical smoke cloud after UAV delivery as the objective, whose expression is:

$$\begin{cases} \overrightarrow{u_M} = \dfrac{\vec{0} - M_{10}}{|M_{10}|} \\ M_1(t) = M_{10} + v_M \cdot t \cdot \overrightarrow{u_M} \\ \overrightarrow{u_{FY_1}} = \dfrac{(0,0,FY_{10z}) - FY_{10}}{|FY_{10}|} \\ FY_1(t) = FY_{10} + v_{FY_1} \cdot t \cdot \overrightarrow{u_{FY_1}} \\ x_e = FY_{1x}(t_e), y_e = FY_{1y}(t_e), z_e = FY_{1z} - \dfrac{1}{2} g{t_e}^2 \\ c(t) = (x_e, y_e, z_e - v_s(t - t_e)) \ , \ t \in [t_e, t_e + 20] \\ \overrightarrow{u_o} = O - M_1(t) \\ \beta = \dfrac{\pi}{2} - art\sin\left(\dfrac{M_{1z}(t)}{M_1(t) - O}\right) \\ u = \dfrac{n \times (d - (n \cdot d)n)}{|n \times (d - (n \cdot d)n)|} \\ v = \dfrac{d - (n \cdot d)n}{|d - (n \cdot d)n|} \\ \dfrac{(r \cdot u)^2}{7^2} + \dfrac{(r \cdot v)^2}{(7\cos\beta)^2} = 1 \ , \ z = 10 \\ |(X - M_1(t)) \times (C - M_1(t))|^2 = R^2 |X - M_1(t)|\|_{z=10} \\ \Delta t = t_p - t_q \end{cases} \tag{1}$$

In the formula, M_{10} is the current coordinate of missile M1, $\overrightarrow{u_M}$ is the unit direction vector of missile M1, v_M is the velocity of the air-to-ground missile, $\overrightarrow{u_{FY_1}}$ is the unit direction vector of the UAV, FY_{10} is the coordinate of $FY1$, u denotes the major axis direction, v denotes the minor axis direction, t_e is the delayed detonation time, t_q is the starting time of shielding, and t_p is the critical time.

By determining the physical boundaries corresponding to the start and end of shielding, this objective function inversely deduces the time instances when the spherical surface is just in contact and when shielding terminates, thereby calculating the total shielding duration.

By determining the physical boundaries corresponding to the start and end of shielding, this objective function inversely deduces $M_1(t_t)$, obtains the time instances when the spherical surface is just in contact and when shielding ends, and calculates the total shielding duration.

2.3 Nonlinear Three-Dimensional Relative Motion Model Based On Los Guidance Law

Based on the LOS guidance law, a nonlinear three-dimensional relative motion model between the UAV and the air-to-ground missile is established, with the heading angle as the objective. Its expression is as follows:

$$\ddot{r} = r\left(\dot{\theta}\right)2\cos\psi + r\left(\dot{\psi}\right)^2 + a_{tr} - a_{mr} \tag{2}$$

$$\ddot{\theta} = -\frac{2\dot{r}\dot{\theta}}{r} + 2\dot{\theta}\dot{\psi}\tan\psi + \frac{a_{t\theta} - a_{m\theta}}{r\cos\psi} \tag{3}$$

$$\ddot{\psi} = \frac{-2\dot{r}\dot{\psi} - r\left(\dot{\theta}\right)^2 \cos\psi \sin\psi + a_{t\psi} - a_{m\psi}}{r} \tag{4}$$

Among them, a_{tr}、 a_{mr} are the accelerations of the UAV and the surface-to-air missile along the line-of-sight direction, respectively. ψ and θ are the relative azimuth angles between the line-of-sight coordinate system $ox_4y_4z_4$ and the reference inertial coordinate system $oxyz$,corresponding to the line-of-sight inclination angle and line-of-sight declination angle, respectively.

2.4 Multi-UAV, Multi-Projectile and Multi-Objective Dynamic Shielding Optimization Model

The multi-UAV, multi-projectile and multi-objective dynamic shielding optimization model aims to maximize the shielding time of three missiles M1, M2, M3 by up to three smoke screen jamming projectiles delivered by five UAVs, and its expression is:

$$\max \ \Delta t\left(\varphi_j, v_{FY_1}, t_{di}, t_{eij}\right) = \left|\bigcup_{i=1}^{3}[t_{pij}, t_{qij}]\right|$$

$$s.t\begin{cases} 70 \leqslant v_{FY_j} \leqslant 140 \\ 0 \leqslant t_{eij} \leqslant 19.1663 \\ t_{eij} \leqslant t \leqslant t_{eij} + 20 \\ t_{eij} \leqslant \dfrac{|M_k|}{v_M} \\ t_{dij} - t_{d(i-1)j} \geqslant 1 \\ \ddot{\psi} \leqslant \varphi_j \leqslant \ddot{\theta} \\ FY_{jix} = c_{ejix} \\ FY_{jiy} = c_{ejiy} \\ FY_{jiz} \geqslant c_{ejiz} \\ if|t_{eij} - t_{ekl}| < 20, |c_{eji} - c_{ekl}| \geqslant 2R \end{cases} \tag{5}$$

In the formula, v_{FY_j} is the velocity of the j-th UAV. t_{eij} is the detonation time of the i-th smoke screen jamming projectile of the j-th UAV. t_{pij} is the shielding start time of the i-th smoke screen jamming projectile of the j-th UAV. t_{qij} is the shielding end time of the i-th smoke screen jamming projectile of the j-th UAV. FY_{jix}、 FY_{jiy}、 FY_{jiz} are the delivery positions of the i-th smoke screen jamming projectile of the j-th UAV. c_{ejix}、 c_{ejiy}、 c_{ejiz} are the detonation positions of the i-th smoke screen jamming projectile of the j-th UAV.

Based on the single-objective model of UAV cooperative smoke jamming projectiles, this function incorporates the constraint of cloud interaction, so as to maximize the shielding time in the multi-UAV, multi-projectile and multi-objective dynamic shielding optimization model.

3. Algorithm Design

Due to the high time complexity of the multi-aircraft, multi-missile, multi-objective model, an improved simulated annealing algorithm is employed. Core design: Initial solution optimization: A greedy algorithm generates a relatively optimal initial solution to avoid the excessive time required by random initialization; Temperature strategy: Initial temperature set to 10 ℃; high-temperature global search in the early stage, followed by local search in the later stage; 100 iterations of cooling during the high-temperature phase; New Solution Generation: The neighborhood strategy first optimizes within a path and then exchanges nodes across paths; solutions violating time constraints are rejected; Local Search: Logarithmic cooling accelerates the cooling rate; an amplification factor is introduced to penalize suboptimal solutions; a termination condition of "consecutive iterations with solution changes less than a threshold" is set to improve convergence efficiency. Verification shows that the improved algorithm reduces computational time, enhances the accuracy of finding optimal solutions, and supports efficient solving in complex scenarios.

4. Result Analysis

4.1 Case Setup

The case is designed for UAVs delivering smoke jamming projectiles, with key parameters as follows: A cylindrical fixed protected target (bottom center (0,200,0), radius 7 m, height 10 m) and a decoy at (0,0,0); three air-to-ground missiles (M1–M3) with initial positions (20000,0,2000), (19000,600,2100), (18000,−600,1900) and speed 300 m/s; five UAVs (FY1–FY5) with initial positions specified, flying at 70–140 m/s (adjustable speed, fixed heading once set), each delivering two smoke projectiles (interval ≥1 s). Detonated projectiles form spherical clouds sinking at 3 m/s, providing effective shielding within 10 m of the center and 20 s post-detonation. These parameters align with actual combat requirements, ensuring case authenticity and representativeness.

4.2 Model Solution Results

4.2.1 Geometric Shielding Judgment Model

The geometric shielding judgment model is calculated through multi-objective dynamic trajectory simulation, geometric shielding judgment and time boundary inversion, and the shielding time is obtained as 1.391 s.

4.2.2 Multi-UAV, Multi-Projectile and Multi-Objective Dynamic Shielding Optimization Model

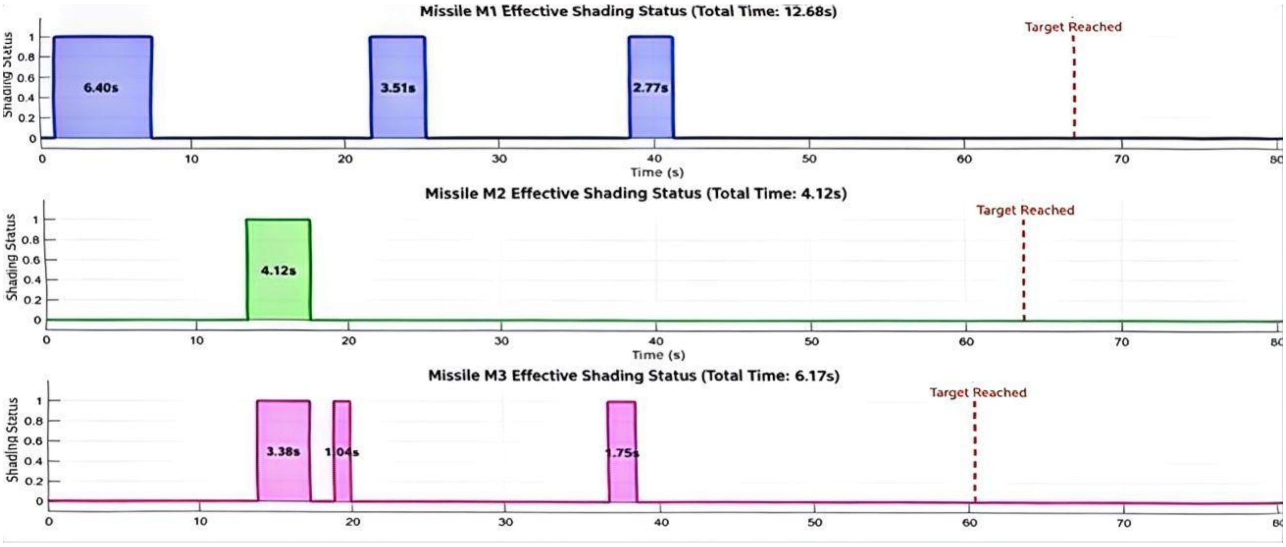


Figure 1: Shielding time of the three missiles

The improved simulated annealing algorithm is used to solve the multi-UAV, multi-projectile and multi-objective dynamic shielding optimization model. The shielding time for the three missiles is shown in Figure 1 and Table 1. Through global exploration in the high-temperature stage and local optimization in the low-temperature stage, the algorithm finally finds a better solution with an effective shielding duration of approximately 22.97 s. This not only verifies the effectiveness of the simulated annealing algorithm in complex optimization problems, but also demonstrates the advantages of the improved algorithm in solution efficiency and solution quality.

Table 1: Model optimization results

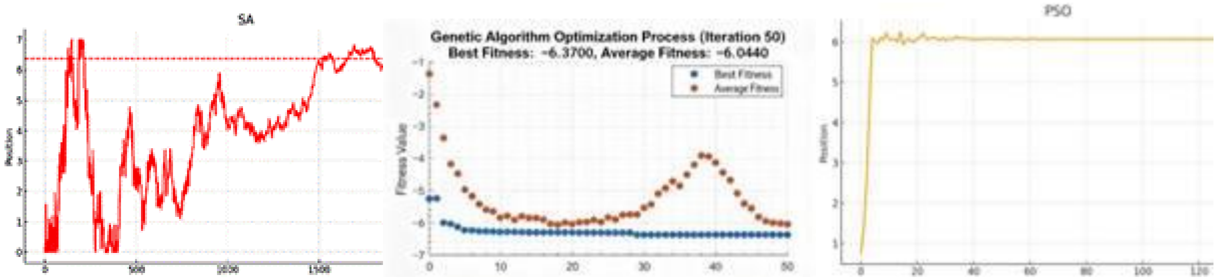
The z-coordinate of the smoke jamming projectile delivery point (m)	The x-coordinate of the smoke jamming projectile detonation point (m)	The y-coordinate of the smoke jamming projectile detonation point (m)	The z-coordinate of the smoke jamming projectile detonation point (m)	Effective jamming duration (s)	Missile number of jamming
1800	17800	0	1800	2.6	1
1800	17903.51	13.53	1799.00	4.5	1
1800	19180.73	180.519	1796.62	0	0
1400	12458.61	419.76	1398.17	4.12	2
1400	12851.56	-420.09	1364.80	3.38	3
1400	13757.48	-2356.39	1137.44	0	0
700	6509.76	-211.24	698.67	1.75	3
700	6555.06	36.61	667.38	2.77	1
700	6564.69	89.26	675.63	0	0
1800	11099.4	2000	1798.77	0	0
1800	11228.2	2000	1791.20	0	0
1800	11239.4	2000	1798.77	0	0
1300	12064.23	-399.99	1286.65	1.04	3
1300	11821.43	15.16	1192.21	3.51	1
1300	11759.01	121.88	1282.49	0	0

4.3 Algorithm Performance Comparison

This paper verifies the effectiveness of three heuristic algorithms (simulated annealing algorithm, particle swarm optimization algorithm, genetic algorithm) using computer simulations.

Table 2: Comparison of model effects

Algorithm	Maximum effective shielding duration	Mean maximum effective shielding duration ±std	Median	Success rate	Time consumption	Feasibility rateFR
SA	6.37	6.22 ±0.09	6.34	0.93	18.2	0.99
PSO	6.13	5.87 ±0.18	6.09	0.57	21.5	0.94
GA	6.05	5.85 ±0.22	6.03	0.50	24.1	0.92



(a) Simulated Annealing Algorithm (b) Genetic Algorithm (c) PSO Algorithm

Figure 2 Performance differences among the three algorithms

Table 2 and Figure 2 show significant performance differences among the three algorithms. Multi-dimensional comparison confirms the simulated annealing algorithm’s prominent advantages, so it is selected as the solution method: (1) Leading solution quality (maximum effective shielding duration of 6.37 s) for easier optimal strategy acquisition; (2) Higher stability (success and feasibility rates than PSO and GA) with few invalid or low-quality solutions; (3) Optimal convergence efficiency with the shortest time for high-quality solution search; (4) Superior convergence characteristics (wide early exploration, fast late convergence), less prone to prematurity than GA and local optimum than PSO, and good robustness despite initial temperature sensitivity.

5. Prospects

5.1 Limitations and Improvement Directions

Research limitations: This model neglects environmental factors such as air resistance and wind field under idealized assumptions, leading to limited adaptability. The complex objective function and numerous parameters require repeated tuning of traditional heuristic algorithms, which tend to trap in local optima and consume significant resources. Future work will introduce environmental and acceleration parameters into the trajectory model and adopt more efficient intelligent optimization algorithms to enhance robustness and reduce computing cost.

5.2 Promotion and Application

The model and technology proposed in this paper have significant promotion value and can be extended to fields such as air-to-ground missile guidance and UAV trajectory planning. To address UAV motion limitations, PID control can be introduced based on the LOS guidance law to build a closed-loop system for flexible speed and direction adjustment, realizing dynamic tracking with target feedback. In the future, parameters and algorithms will be optimized according to actual needs to promote engineering implementation and support the improvement of equipment motion control performance.

6. Conclusions

Based on mechanism-driven model construction and algorithm improvement, this paper concludes: The established model has a clear mechanism and conforms to actual laws, using missile vertex as point light source and spherical cloud as light cone for geometric analysis to provide reliable support for trajectory and shielding problems. The improved traditional simulated annealing algorithm achieves accurate and efficient solutions with less resource consumption. The introduced LOS guidance law narrows useless constraints, provides better initial values and scientific disturbance directions, realizing mechanism-driven computing power saving and improving solution accuracy and efficiency.

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