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Multi-UAV Smoke Decoy Deployment Strategy and Hierarchical Optimization in Cooperative Defense Scenarios

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ABSTRACT

To counter the threat posed by incoming missiles to critical military targets, this study systematically analyzes optimization strategies for deploying smoke-generating decoys via unmanned aerial vehicles (UAVs). Considering that smoke-screen performance is closely related to the physical characteristics of dispersed particulate media, which in some applications may involve fibrous or textile-derived materials, the research first constructs a three-dimensional kinematic model to precisely describe the relative spatial trajectories of missiles, UAVs, and smoke clouds, establishing the physical boundaries for effective concealment using analytical geometric criteria. Building upon foundational effectiveness evaluations, the study introduces a simulated annealing algorithm for global optimization of flight direction, velocity, and deployment timing in single-platform interception tasks, significantly enhancing the shielding efficacy of individual munitions. Subsequently, addressing higher-dimensional challenges of multi-munition coordination and multi-UAV formation operations, a genetic algorithm-based optimization framework is established. This framework achieves precise temporal and spatial sequencing of multiple smoke grenades through a time-window matching model. Particularly in complex decision scenarios involving simultaneous missile attacks, the model synchronously schedules the flight paths and payload timing of five UAVs using high-dimensional decision variables, ensuring maximum coverage during multi-target interception missions. Simulation results demonstrate that this hierarchical, progressive optimization strategy provides scientific quantitative support for defense decisions in complex battlefield environments.

KEYWORDS
fibrous particulate medium, smoke jammer, coordinated deployment strategy, heuristic algorithm

INTRODUCTION

As cruise missiles advance in penetration capabilities and accuracy, modern warfare poses severe challenges to the protection of critical military targets. Smoke jammers, with their low cost and high cost-effectiveness, have become an indispensable passive defense measure. The effectiveness of smoke-screen systems is inherently influenced by the dispersion behavior and optical properties of the released medium, which, in certain implementations, may involve fibrous or textile-derived particulate structures. Although unmanned aerial vehicles (UAVs) provide mobility support for the precise deployment of smoke grenades at designated points, coordinating multiple deployment nodes in dynamic three-dimensional space to achieve optimal target interception duration remains a critical technical challenge. Previous studies have predominantly focused on evaluating effectiveness in static backgrounds or with single munitions, often neglecting the temporal synchronization and spatial motion coupling inherent in multi-platform coordination[1]. The innovation of this section lies in proposing a hierarchical progressive optimization framework integrating kinematic modeling and heuristic search, achieving a technological leap from single-point qualitative assessment to quantitative decision-making in complex multi-to-multi scenarios. The general research approach first establishes the dynamic equations for missiles and UAVs using a spatial Cartesian coordinate system, defines the masking state using the distance criterion between a point and a line, employs simulated annealing to rapidly optimize low-dimensional parameters, and further utilizes the evolutionary mechanism of genetic algorithms to handle high-dimensional coordination variables in multi-aircraft formations[2-3]. Finally, a multi-missile masking time window matching model is implemented to achieve effective interference throughout the enemy ‘s terminal guidance phase[4-5].

MODEL ESTABLISHMENT AND SOLUTION

Calculating Fixed-Parameter Smoke Screen Duration for Single-Drone Single-Smoke-Screen Deployment

Model Establishment

A spatial rectangular coordinate system is established with the decoy target as the origin, as shown in Figure 1. The initial coordinates of missile M1 are (20000, 0, 2000), its flight speed is 300 m/s, and its flight direction points from its initial position to the origin. The initial coordinates of UAV FY1 are (17800, 0, 1800), its flight speed is 120 m/s, and it flies at a constant altitude horizontally along the x-axis. UAV FY1 flies along the initial route for 1.5 s before launching one smoke jamming bomb, which detonates after an interval of 3.6 s[6-7].

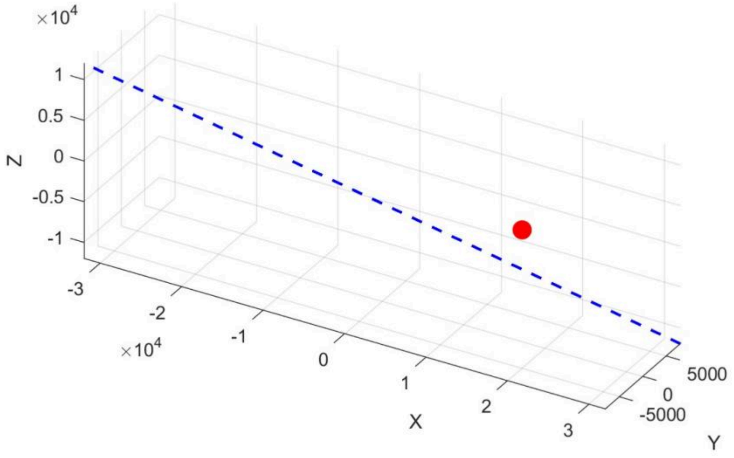

Figure 1. Schematic diagram of the spatial rectangular coordinate system for the relative positions of smoke clouds, missiles, and real targets

The bomb release time $t_d = 1.5$ s and the detonation time $t_b = 5.1$ s. This process is divided into three stages:

$0 \sim t_d$: The smoke bomb is not released and flies with UAV FY1 at a constant altitude and speed;

$t_d \sim t_b$: The UAV releases the smoke bomb, which performs a horizontal projectile motion with the same initial velocity as UAV FY1;

$t_b \sim t_v$: The smoke bomb detonates, forming a smoke cloud that descends uniformly at 3 m/s with an effective radius of 10 m, lasting for 20 s, and dissipates instantly after 20 s. It should be noted that the 10m effective radius is a baseline parameter based on a typical single smoke jamming bomb. While the interference window for a single cloud might be extremely small against high-speed missiles (300 m/s) and UAVs (120 m/s), the core of this study is the coordinated deployment of multiple UAVs and munitions. By forming a continuous shielding chain in both time and space, the limitations of a single cloud's coverage are effectively mitigated. The optimization strategy proposed in this paper is specifically designed to find the optimal timing and coordinates under these rigorous conditions to achieve sustained protection of the target.

A straight line L is drawn connecting missile M1 and the real target P . Taking the center Q_1 of the smoke cloud as the research object, the distance d from Q_1 to the straight line L is calculated to determine whether the smoke cloud effectively shields the real target. If $d \leq 10$ m, the shielding is considered effective; otherwise, it is not.

Model Solution

During the period $0 \sim t_b$, missile M1 continues to fly uniformly towards the decoy target with $v_M = 300$ m/s, and the distance traveled $S_M = v_M \cdot t_b = 1530$ m. Since the ratio $x_M : z_M = 10 : 1$ remains constant, we have:

$$\cos\theta = \frac{10}{\sqrt{101}}, \sin\theta = \frac{1}{\sqrt{101}} \tag{1}$$

$$\Delta x = 1530 \cdot \cos\theta = 1522.41\,\mathrm{m}, \Delta z = 1530 \cdot \sin\theta = 152.24\,\mathrm{m} \tag{2}$$

Subtracting the increments from the initial coordinates (20000 - Δx , 0, 2000 - Δz), the coordinates of M1 at this time are (18477.59, 0, 1847.76)[8-9].

During the period $0 \sim t_d$, the UAV carries the smoke bomb and flies towards the decoy target at $v_{FY1} = 120$ m/s. The horizontal displacement $\Delta x = v_{FY1} \cdot t_d = 180$ m. Subtracting the increment from the initial position of UAV FY1 (17800 - 180, 0, 1800), the coordinates of FY1 at this time are (17620, 0, 1800).

During the period $t_d \sim t_b$, the smoke bomb detaches from the UAV and performs a horizontal projectile motion. In the horizontal direction, the smoke bomb moves uniformly with $\Delta x = 432$ m; in the vertical direction, it performs free fall motion with:

$$\Delta z = \frac{1}{2} g t_{\mathrm{delay}}^2 = 63.504\,\mathrm{m} \tag{3}$$

By summing and subtracting the displacement increments from the release position coordinates of the smoke bomb, the coordinates of the smoke bomb Q_1 at this time are (17188, 0, 1736.496).

During the period $t_b \sim t_v$, the smoke bomb explodes to form a smoke cloud. At this time:

$$X_{M1} = 18477.59 - 298.51t, Y_{M1} = 0, Z_{M1} = 1847.76 - 29.85t \tag{4}$$

$$X_{Q1} = 17188, Y_{Q1} = 0, Z_{Q1} = 1736.496 - 3t \tag{5}$$

The parametric equation of line L is:

$$\frac{x}{18477.59-298.51t}=\frac{y-200}{-200}=\frac{z-5}{1842.76-29.85t} \tag{6}$$

The vector $\overrightarrow{PQ1}=(17188,-200,1731.496-3t)$ and the direction vector of line L $\vec{S}=(18477.59-298.51t,-200,1842.76-29.85t)$. The cross product $\vec{S}\times\overrightarrow{PQ1}$ is:

$$\vec{S}\times\overrightarrow{PQ1}=(600t-346299.2)\vec{\imath}+(-320514.2946+59222.6677t-895.5335t^2)\vec{\jmath}+(-257918+59702.2314t)\vec{k} \tag{7}$$

The distance d from point $Q1$ to line L is:

$$d=\frac{\parallel\vec{S}\times\overrightarrow{PQ1}\parallel}{\parallel\vec{S}\parallel} \tag{8}$$

Define the shielding state function:

$$f(t)=\begin{cases}1 \text{ if } \ d\leq 10\,\mathrm{m} \text{ and } \ t_b\leq t\leq t_v\\ 0 \text{ otherwise}\end{cases} \tag{9}$$

Although the objective function is currently set to maximize the total shielding duration, the simulation is initialized with the missile at a critical distance of 20 km. Given the limited duration of the smoke screen and the high speed of the incoming missile, the algorithm inherently seeks optimal solutions within the terminal guidance phase window. Thus, the model implicitly prioritizes the most critical interference timing during the missile’s final approach. where an output of 1 indicates effective shielding of the missile by the smoke, and 0 indicates no effective shielding. Setting the time step $\Delta t=0.01$ s, the integral of all satisfying $f(t)$ gives the effective shielding time T_{11} . Through program traversal calculation, the result is $T_{11}=1.42$ s.

Parameter Optimization for Single-Drone Single-Smoke-Screen Deployment (Maximizing Duration)

Model Establishment

Given the large-scale parameter search space involved in multi-munition deployment, this study utilizes a Genetic Algorithm (GA) for strategy optimization. The algorithm encodes UAV velocity, heading, and the deployment timing of each smoke bomb into chromosomal genes, employing selection, crossover, and mutation operators to perform parallel searches in a multi-dimensional space, thereby rapidly approaching the global optimal deployment scheme under complex nonlinear constraints[10-12] (Figure 2).

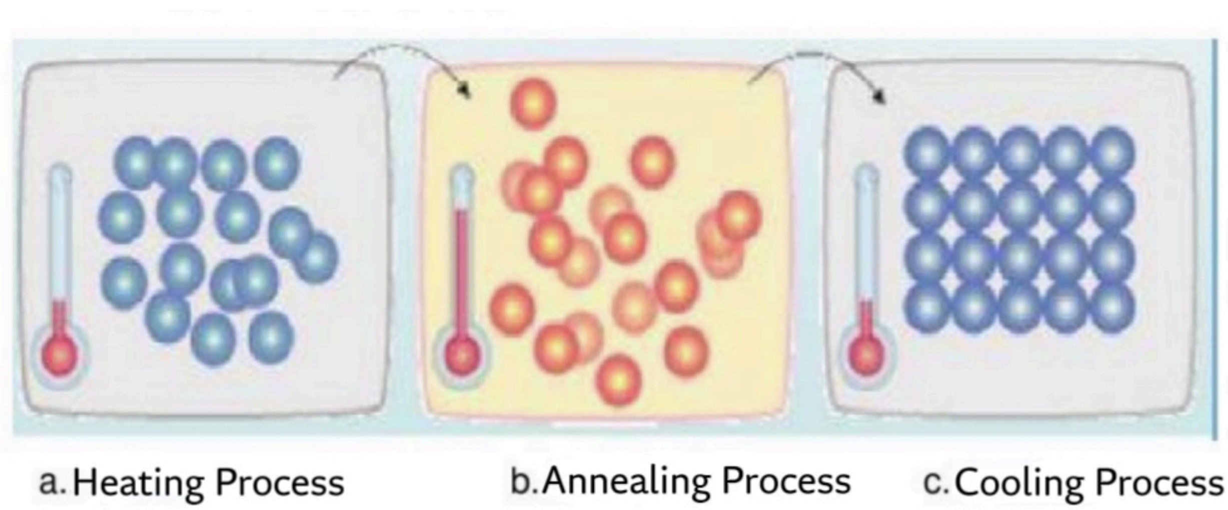

Figure 2. Physical annealing process

The simulated annealing algorithm attempts to start from an initial solution and gradually search for other possible solutions to find the global optimal solution. Its working principle is as follows:

Randomly select an initial solution and initial temperature;

Randomly perturb the solution at the current temperature to generate a new solution[13];

Calculate the objective function values of the new solution and the old solution:

If the new solution is better, accept the new solution;

If the new solution is not better, accept it with a certain probability (i.e., there is a possibility of "escaping local optima"), where the probability depends on the current temperature and the quality of the solution.

Gradually decrease the temperature with each iteration;

Terminate when the termination condition is met (e.g., reaching the maximum number of iterations or the temperature dropping to a certain threshold). Flowchart of the simulated annealing algorithm is shown in figure 3.

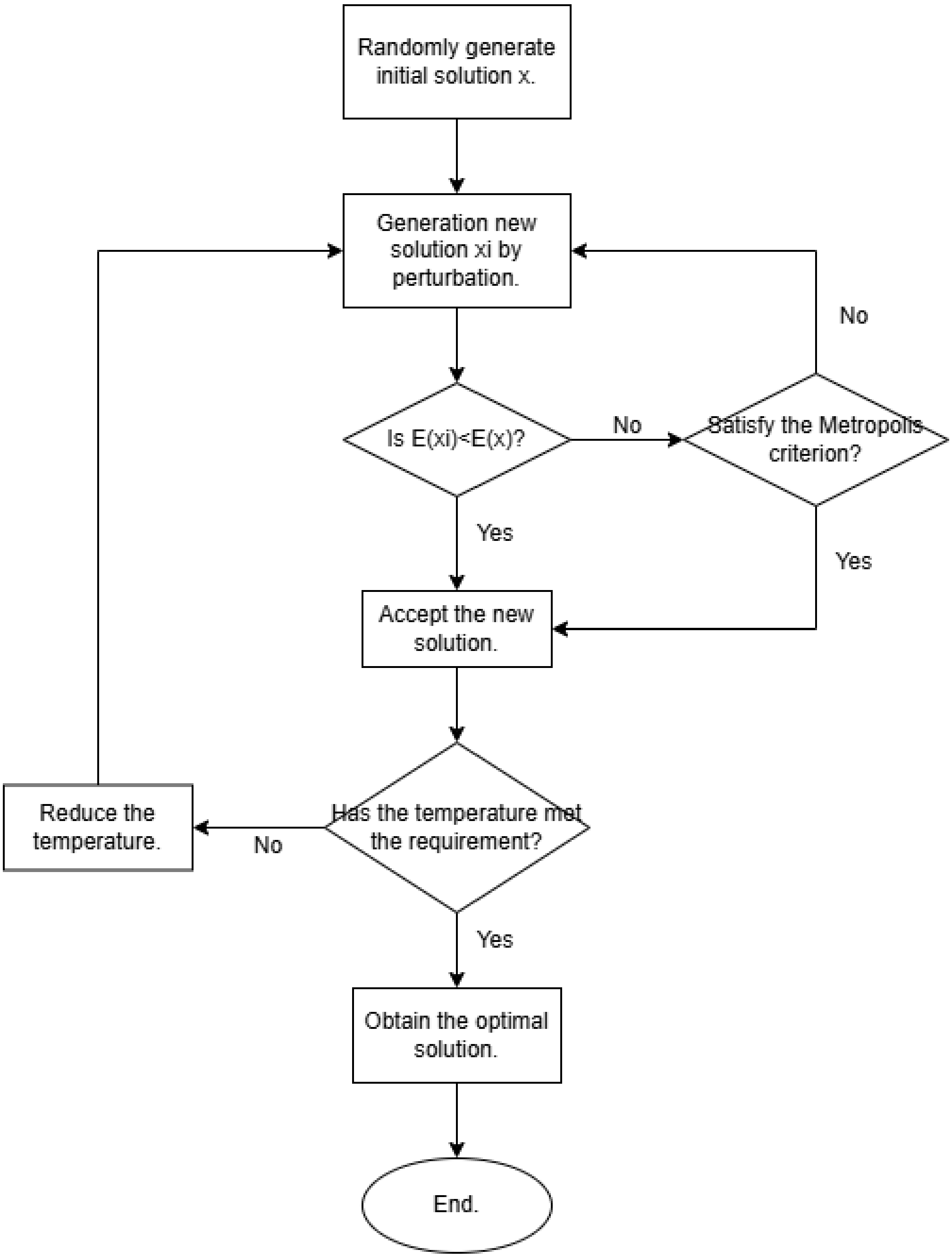

Figure 3. Flowchart of the simulated annealing algorithm

Model Solution

Initialization

Set an initial temperature T_0 and an initial solution x_0 for the problem;

Select one from multiple feasible solutions as the initial solution;

Obtain a better initial solution using the Monte Carlo method[14-15];

For this problem, the flight speed, flight direction, smoke bomb release time, and smoke bomb detonation time of the UAV are used as the initial solution:

In this problem, UAV FY1 flies towards the decoy target, with the initial yaw angle ϕ_0 , flight speed $v_0 = 120$ m/s. Assuming the initial time is 0, the bomb release time $t_{d0} = 1.5$ s, and the smoke jamming bomb detonation time $t_{b0} = 1.5$ s + 3.6 s = 5.1 s.

Randomly Generate New Solutions

Assume the solution from the previous step is: $\phi_{i-1}, v_{i-1}, t_{d(i-1)}, t_{b(i-1)}$

Randomly find a solution x' at the current temperature T_i and formulate criteria for generating new solutions (the criteria are not unique, but must be random). In this paper, x' is as follows: $\phi_i, v_i, t_{di}, t_{bi}$

Calculate the Difference in Objective Function

For the randomly obtained solution x' and the current solution $x(i)$, the difference in shielding time between the two schemes is denoted as Δf :

$$\Delta f = [-T_h(\phi_i, v_i, t_{di}, t_{bi})] - [-T_h(\phi_{i-1}, v_{i-1}, t_{d(i-1)}, t_{b(i-1)})] \tag{10}$$

To ensure the difference Δf of the objective function matches the following acceptance criteria, the negative of the objective function T_h is used for the difference calculation.

Accept or Reject the New Solution

Acceptance criteria:

$$P = \begin{cases} 1 & \text{if } \ \Delta f < 0 \\ exp(-\Delta f / T_i) & \text{if } \ \Delta f \geq 0 \end{cases} \tag{11}$$

The judgment criterion $exp(-\Delta f / T_i)$ in the expression is inspired by thermodynamics.

This paper requires the longest shielding time. If $\Delta f < 0$, it means the shielding time of solution x' is longer, so x' is accepted as the new solution, and $x(i) = x'$;

If $\Delta f \geq 0$, it means the shielding time of solution x' is shorter than the original solution $x(i)$, but to avoid falling into a local optimal solution, x' is still accepted with a certain probability.

Markov Process

Repeat steps 2, 3, and 4 at the current temperature T_i ;

When the temperature T_i is constant, $exp(-\Delta f/T_i)$ in the judgment criterion is determined by Δf , which is determined by the random solution x' and the current solution $x(i)$;

Therefore, the new solution $x(i+1)$ is only related to $x(i)$, not to earlier solutions such as $x(i-1), x(i-2), ..., x(0)$;

The above process is a Markov process, and x' follows a uniform distribution in the neighborhood of the original solution $x(i)$.

Annealing Process

Select a cooling coefficient α to obtain the new temperature $T_{i+1} = \alpha T_i$ (where α approaches 1 from the left);

Repeat steps 2, 3, 4, and 5 to continue decreasing the temperature.

Termination Condition

Terminate the iteration when the temperature is sufficiently low (assuming the termination temperature $e = 10^{-30}$), and output the final solution when $T < e$.

Through Python simulation calculation, UAV FY1 flies at a speed of $v_{FY1} = 120.36$ m/s along the vector (-0.9998, 0.0186, 0); the smoke jamming bomb release position is (17619.49, 3.36, 1800); the smoke jamming bomb detonation position is (17186.27, 11.42, 1736.496).

Optimization of Coordinated Deployment Strategy for One Drone and Three Smoke Grenades

Model Establishment

In the hierarchical optimization framework of this study, Simulated Annealing (SA) is employed for low-dimensional parameter searches in single-platform tasks due to its rapid convergence. In contrast, for high-dimensional decision spaces involving multi-UAV and multi-munition coordination, the Genetic Algorithm (GA) is selected for its superior parallel search capabilities and global robustness, effectively avoiding local optima in complex collaborative tasks. Considering the large parameter space of the model, this study adopts the optimization strategy of the Genetic Algorithm (GA). As a bionic intelligent optimization method, the core idea of the genetic algorithm is derived from the natural selection and genetic mutation mechanism in Darwin’s theory of evolution. The algorithm encodes the parameters to be optimized into chromosome-like structures (such as binary strings), and continuously optimizes the population quality through simulating selection, crossover, and mutation operations in the biological evolution process, thereby achieving a gradual approximation to the optimal solution of complex problems.

The flow of the genetic algorithm mainly includes: initializing the population, calculating fitness, selection operation, crossover operation, mutation operation, updating the population, and judging the termination condition[16].

Its basic steps are shown in the following figure 4:

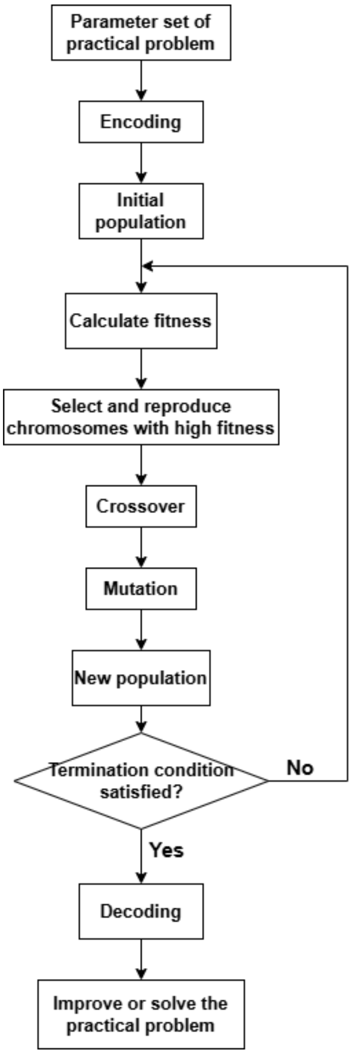

Figure 4. Basic steps of the genetic algorithm

The genetic algorithm adopts an iterative mechanism to optimize the parameters of the objective function and terminates the calculation process when the objective function value meets the preset condition. The iterative process of the algorithm does not depend on the continuity characteristics of the objective function, i.e., it does not need to use gradient information or other mathematical properties based on continuity. Its core idea is to analogize the set of parameters to be optimized as biological chromosomes, where each parameter is regarded as a gene on the chromosome, and the objective function is interpreted as the fitness evaluation function of the individual to the living environment. Schematic diagram of genes, chromosomes, and populations are shown in figure 5.

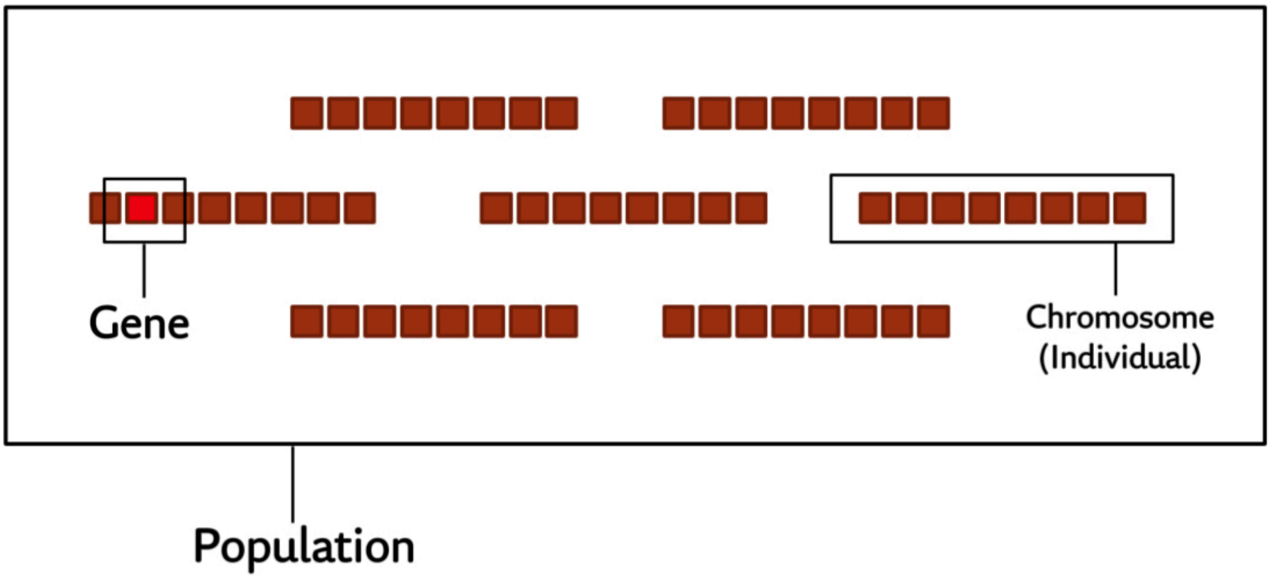

Figure 5. Schematic diagram of genes, chromosomes, and populations

The main operations of the genetic algorithm are as follows:

Selection: The selection operation simulates the natural selection mechanism, whose function is to screen excellent individuals from the current population to give them more opportunities to pass their genes to the next generation. Common selection strategies include roulette wheel selection, tournament selection, etc[15-16].

Roulette wheel selection: Determine the area size of the individual on the selection wheel according to the proportion of the individual’s fitness in the total fitness of the population. The individual is selected by generating a random number and determining the area it falls into. Individuals with higher fitness have larger corresponding areas and a higher probability of being selected.

Tournament selection: Randomly select several individuals from the population to form a competition group each time, and select the individual with the highest fitness to enter the next generation. Repeat this process until the required number of individuals is selected.

Crossover: The crossover of gene loci with equal probability derives new genotypes, similar to genetic recombination in the biological reproduction process. Common crossover methods include single-point crossover, multi-point crossover, and uniform crossover.

Single-point crossover: Randomly select a crossover point on two parent chromosomes and exchange the genes after the crossover point to generate two new offspring individuals.

Multi-point crossover: Select multiple crossover points and exchange genes between these crossover points[17-18].

Uniform crossover: Exchange each gene locus according to a certain probability. Schematic diagram of the crossover operation is shown in figure 6.

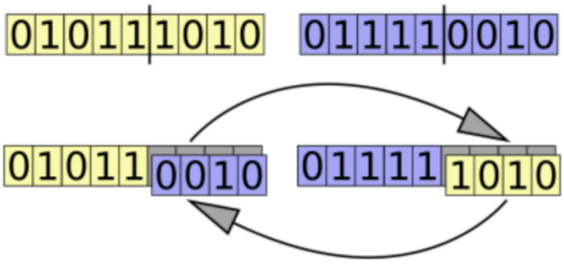

Figure 6. Schematic diagram of the crossover operation

Mutation: Randomly change certain genes of the individual to introduce new gene combinations, simulating gene mutation in the biological evolution process. In the genetic algorithm, the mutation probability is usually low to avoid destroying the already good gene structure. Schematic diagram of the mutation operation is shown in figure 7.

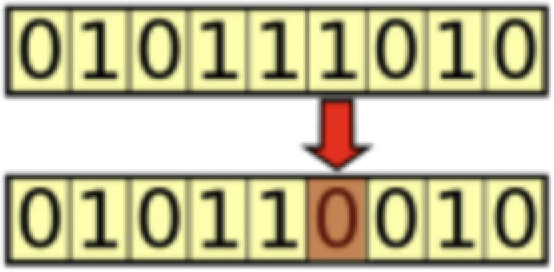

Figure 7. Schematic diagram of the mutation operation

Model Solution

For the case of multiple smoke jamming bombs interfering with a single missile, d and $f(d)$ are revised as follows:

Let d_i denote the distance from the i-th smoke jamming bomb to the line connecting the first missile and the real target:

$$d_i = \begin{cases} \frac{\|\vec{S} \times \overrightarrow{PQi}\|}{\|\vec{S}\|} & \text{if} \quad t_{d(i)} \leq t \leq t_{b(i)} \\ +\infty & \text{otherwise} \end{cases} \tag{12}$$

The shielding state function:

$$f(d) = \begin{cases} 1 \text{ if } \quad d_1 < 10 \quad \text{or} \quad d_2 < 10 \quad \text{or} \quad d_3 < 10 \\ 0 \text{ otherwise} \end{cases} \tag{13}$$

Since d_i is a function of t , the integral of t can be performed, where T_1 represents the time that missile 1 is shielded:

$$T_1 = \int_{t_{\text{start}}}^{t_{\text{end}}} f(d(t))dt \tag{14}$$

Considering the large parameter space of the model, this study adopts the optimization strategy of the genetic algorithm. As a bionic intelligent optimization method, the core idea of the genetic algorithm is derived from the natural selection and genetic mutation mechanism in Darwin's theory of evolution. The algorithm encodes the parameters to be optimized into chromosome-like structures (such as binary strings), and continuously optimizes the population quality through simulating selection, crossover, and mutation operations in the biological evolution process, thereby achieving a gradual approximation to the optimal solution of complex problems[19-20].

Population Initialization

Treat the following 8 variables as 8 genes of an individual: the speed magnitude v_{FY1} and speed direction ϕ_{FY1} of FY1, and the release times t_{d1}, t_{d2}, t_{d3} and detonation times t_{b1}, t_{b2}, t_{b3} of Q1, Q2, Q3 respectively. Treat this set of variables as an individual. Since UAV FY1 launches 3 smoke jamming bombs Q1, Q2, Q3 successively and maintains constant altitude and speed during this period, the initial velocity magnitude and direction of Q1, Q2, Q3 are consistent;

It is now necessary to represent the possible values of these eight variables with binary numbers. According to the decision variable constraints, the number of bits of the required binary numbers is as follows: v_{FY1} requires 8 bits, ϕ_{FY1} requires 9 bits, and $t_{d1}, t_{d2}, t_{d3}, t_{b1}, t_{b2}, t_{b3}$ each require 7 bits. Thus, a binary array with a capacity of 59 can be used as an individual. Randomly generate multiple individuals (arrays) to obtain a population (solution set);

Repeat the previous step to generate multiple individuals to form a population (solution set).

Selection Operation

Calculate the fitness of each individual: Bring each individual (array) into the objective function $T_1(\phi_{FY1}, v_{FY1}, t_{d1}, t_{d2}, t_{d3}, t_{b1}, t_{b2}, t_{b3})$, where T_1 represents the total shielding time of the 3 smoke jamming bombs on missile M1 under different time sequences. The purpose is to select excellent individuals from the k-th generation population and pass their genes to the next generation population. The selection follows two principles: individuals with higher fitness have a higher probability of being selected; individuals with lower fitness still have a chance of being selected.

Select individuals using the roulette wheel method:

Calculate the probability $P(x_i)$ of each individual being selected, where the probability value is proportional to its fitness value;

Calculate the cumulative probability q_i corresponding to each individual, which is the sum of the probabilities of being selected from the first individual to the current individual:

$$P(x_i) = \frac{T_1(\phi_{FY1i}, v_{FY1i}, t_{d1i}, t_{d2i}, t_{d3i}, t_{b1i}, t_{b2i}, t_{b3i})}{\sum_{j=1}^{N} T_1(\phi_{FY1j}, v_{FY1j}, t_{d1j}, t_{d2j}, t_{d3j}, t_{b1j}, t_{b2j}, t_{b3j})} \tag{15}$$

$$q_i = \sum_{j=1}^{i} P(x_j) \tag{16}$$

Randomly generate an array bet, where each element in the array takes a value between 0 and 1, and sort it in ascending order;

If the cumulative probability q_i of the i-th individual is greater than $bet(i)$, the i-th individual is selected, and $bet(i)$ is updated to $bet(i+1)$; otherwise, the (i+1)-th individual is selected to compare with $bet(i)$ until an individual is selected;

Repeat step 4 until the number of selected individuals is equal to the population size (individuals are allowed to be selected multiple times).

Crossover Operation

Perform crossover operations between two individuals among all selected individuals. First, determine whether to perform the crossover operation according to the crossover probability (generally set to 80% to 90%), randomly select the crossover position, and exchange the binary numbers at the corresponding positions.

Iterative Loop

Select the new generation population (solution set) obtained after crossover and mutation, and record the optimal individual and optimal fitness of this iteration;

Repeat the selection operation, crossover operation, and mutation operation.

Through Python simulation calculation, the results are as table 1:

Table 1. Solution results

UAV movement direction	UAV movement speed (m/s)	Smoke jamming bomb number	x-coordinate of smoke jamming bomb release point (m)	y-coordinate of smoke jamming bomb release point (m)	z-coordinate of smoke jamming bomb release point (m)	x-coordinate of smoke jamming bomb detonation point (m)	y-coordinate of smoke jamming bomb detonation point (m)	z-coordinate of smoke jamming bomb detonation point (m)	Effective jamming duration (s)
(−79.06, 1.93, 0)	79.08	1	17797.63	0.06	1800	17588.44	5.17	1765.69	4.43
(−79.06, 1.93, 0)	79.08	2	17637.06	3.98	1800	17367.40	10.56	1742.99	3.96
(−79.06, 1.93, 0)	79.08	3	17312.62	11.90	1800	17206.60	14.49	1791.19	2.12

Note: With the x-axis as the positive direction and counterclockwise as positive, the value ranges from 0 to 360 (degrees).

Optimization of Coordinated Deployment Strategy for Three Drones and One Smoke Grenade

Model Establishment

This problem continues the analysis idea of the optimal shielding position. Based on the optimal detonation position model of a single smoke jamming bomb, it further studies the connection mechanism of multiple smoke jamming bombs in the time sequence. By establishing a multi-bomb shielding time window matching model, it optimizes the flight parameters of each UAV and the bomb release and detonation time sequence, so that the shielding time periods formed by the 3 smoke jamming bombs can cover the critical stage of the missile approaching the real target as much as possible.

Model Solution

This problem involves 3 UAVs each launching 1 smoke jamming bomb to interfere with the missile. Now, d and $f(d)$ are revised as follows:

Let d_i denote the distance from the smoke jamming bomb launched by the i-th UAV to the line connecting the first missile and the real target:

$$d_i = \begin{cases} \frac{\|\vec{S} \times \overrightarrow{PQi}\|}{\|\vec{S}\|} \text{ if } \ t_{d(i)} \le t \le t_{b(i)} \\ +\infty \qquad \text{otherwise} \end{cases} \tag{17}$$

The shielding state function:

$$f(d) = \begin{cases} 1 \text{ if } \ d_1 < 10 \ \text{ or } \ d_2 < 10 \ \text{ or } \ d_3 < 10 \\ 0 \text{ otherwise} \end{cases} \tag{18}$$

Since d_i is a function of t , the integral of t can be performed, where T_1 represents the time that missile 1 is shielded:

$$T_1 = \int_{t_{\text{start}}}^{t_{\text{end}}} f(d(t))dt \tag{19}$$

This problem continues the analysis idea of the optimal shielding position and uses the genetic algorithm to solve the problem. Since the flight speed direction and speed magnitude of FY1, FY2, and FY3 can be different, there are the following 12 variables at this time: the speed magnitude v_{FY1} and speed direction ϕ_{FY1} of FY1, the speed magnitude v_{FY2} and speed direction ϕ_{FY2} of FY2, the speed magnitude v_{FY3} and speed direction ϕ_{FY3} of FY3, the release times t_{d1}, t_{d2}, t_{d3} and detonation times t_{b1}, t_{b2}, t_{b3} of the smoke jamming bombs launched by FY1, FY2, FY3 respectively; treat these 12 variables as 12 genes of an individual, and treat this set of variables as an individual. Moreover, since $v_{FY1}, v_{FY2}, v_{FY3}$ each need to be represented by 8-bit binary numbers, $\phi_{FY1}, \phi_{FY2}, \phi_{FY3}$ each need to be represented by 9-bit binary numbers, and $t_{d1}, t_{d2}, t_{d3}, t_{b1}, t_{b2}, t_{b3}$ each need to be represented by 7-bit binary numbers, an individual can be represented by a binary array with 93 elements. Subsequently, randomly generate multiple individuals to form a population.

Through Python simulation calculation, the results are as table 2:

Table 2. Solution results

UAV number	UAV movement direction	UAV movement speed (m/s)	x-coordinate of smoke jamming bomb release point (m)	y-coordinate of smoke jamming bomb release point (m)	z-coordinate of smoke jamming bomb release point (m)	x-coordinate of smoke jamming bomb detonation point (m)	y-coordinate of smoke jamming bomb detonation point (m)	z-coordinate of smoke jamming bomb detonation point (m)	Effective jamming duration (s)
FY1	(−78.77, 70.93, 0)	106	17169.81	567.42	1800	16618.40	1063.92	1559.90	3.46
FY2	(−77.75, 83.37, 0)	114	11533.51	1900.25	1400	11067.03	2400.49	1223.60	4.08
FY3	(−64.60, 66.90, 0)	93	5418.57	−2397.91	700	5030.95	−1996.52	523.60	1.41

Note: With the x-axis as the positive direction and counterclockwise as positive, the value ranges from 0 to 360 (degrees).

Optimization of Composite Obfuscation Strategy for Five Drones and Multiple Smoke Grenades Against Multiple Missiles

Model Establishment

This problem continues the analysis idea of the optimal shielding position. Based on the optimal flight parameter model of a single UAV and the optimal detonation position model of single and multiple smoke jamming bombs, it further studies the connection mechanism of multiple UAVs launching multiple smoke jamming bombs in the time sequence. By establishing a multi-bomb shielding time window matching model, it optimizes the flight parameters of each UAV and the detonation time sequence of each smoke jamming bomb, so that the shielding time periods of the smoke clouds formed by all smoke jamming bombs can cover the critical stages of the 3 missiles approaching the real target as much as possible.

Model Solution

For the case of multiple smoke bombs interfering with multiple missiles, d and $f(d)$ are revised as follows:

Let d_{ijp} denote the distance from the j-th (j=1,2,3) smoke bomb launched by UAV FYi (i=1,2,3,4,5) to the line connecting the p-th (p=1,2,3) missile Mp and the real target:

$$d_{ijp} = \begin{cases} \frac{\|\vec{S}\times\overrightarrow{PQj}\|}{\|\vec{S}\|} \text{ if } \ t_{d(j)} \le t \le t_{b(j)} \\ +\infty \qquad \text{otherwise} \end{cases} \tag{20}$$

The shielding state function for missile Mp:

$$f_p(d) = \begin{cases} 1 \text{ if } \ d_{11p} < 10 \ \text{ or } \ d_{21p} < 10 \ \text{ or } \ ... \ \text{ or } \ d_{51p} < 10 \\ 0 \text{ otherwise} \end{cases} \tag{21}$$

The total effective shielding time T for the real target (the real target is considered shielded only when all missiles are shielded):

$$T = \int_{t_{\text{start}}}^{t_{\text{end}}} \prod_{p=1}^{3} f_p(d(t))dt \tag{22}$$

Through Python simulation calculation, the results are as table 3:

Table 3. Solution results

UAV number	UAV movement direction	UAV movement speed (m/s)	Smoke jamming bomb number	x-coordinate of smoke jamming bomb release point (m)	y-coordinate of smoke jamming bomb release point (m)	z-coordinate of smoke jamming bomb release point (m)	x-coordinate of smoke jamming bomb detonation point (m)	y-coordinate of smoke jamming bomb detonation point (m)	z-coordinate of smoke jamming bomb detonation point (m)	Effective jamming duration (s)	Interfered missile number
FY1	(−123.48,-28.96,0)	126.83	1	17654.02	−42.53	1800	17189.87	−147.68	1741.11	2.63	1
FY1	(−123.48,-28.96,0)	126.83	2	17522.31	−79.84	1800	17051.54	−182.37	1759.76	2.8	1
FY1	(−123.48,-28.96,0)	126.83	3	17453.49	−63.98	1800	17263.74	−159.76	1739.89	2.72	1
FY2	(−33.25,115.95,0)	120.62	1	11903.21	1109.11	1400	11685.06	623.28	1323.34	1.48	2
FY2	(−33.25,115.95,0)	120.62	2	11824.57	908.05	1400	11602.47	478.52	1340.54	1.54	2
FY2	(−33.25,115.95,0)	120.62	3	11786.59	1126.01	1400	11655.38	531.62	1338.98	1.52	2
FY3	(29.12,108.68,0)	112.51	1	6085.44	−2619.45	700	6201.56	−2178.54	615.88	1.02	3
FY3	(29.12,108.68,0)	112.51	2	6130.21	−2389.38	700	6252.57	−2037.92	638.46	1.08	3
FY3	(29.12,108.68,0)	112.51	3	6189.04	−2234.89	700	6312.49	−1905.64	646.04	1.12	3
FY4	(−96.74,-81.18,0)	126.29	1	10711.56	1812.89	1800	10392.55	1500.69	1731.28	2.28	2
FY4	(−96.74,-81.18,0)	126.29	2	10621.28	1743.22	1800	10213.68	1405.28	1750.12	2.85	2
FY4	(−96.74,-81.18,0)	126.29	3	10669.63	1789.62	1800	10259.36	1478.45	1733.96	2.74	2
FY5	(−109.65,51.13,0)	120.98	1	12721.82	−1842.04	1300	12242.74	−1654.93	1218.01	2.48	3
FY5	(−109.65,51.13,0)	120.98	2	12612.33	−1795.68	1300	12165.88	−1602.76	1239.23	2.56	3
FY5	(−109.65,51.13,0)	120.98	3	12696.48	−1821.06	1300	12235.14	−1638.95	1226.07	2.52	3

Note: With the x-axis as the positive direction and counterclockwise as positive, the value ranges from 0 to 360 (degrees).

CONCLUSIONS

By constructing a multidimensional smoke-screen interference coordination model, this research systematically resolves a series of decision-making problems—from single-aircraft baseline performance evaluation to multi-aircraft, multi-target interception in complex scenarios. Through the integrated application of simulated annealing and genetic algorithms, the study quantitatively determines optimal flight paths and bomb detonation parameters under various operational configurations, significantly enhancing the system's ability to counter incoming missiles. The results indicate that optimizing the spatiotemporal deployment of smoke clouds is a key factor in improving shielding effectiveness, which may also provide a useful reference for the deployment of particulate media with similar dispersion characteristics. Although the model demonstrates strong engineering applicability in analytical decision-making and multi-level optimization, its adaptability to real battlefield environments remains limited.The simplification of smoke as 'dissipating instantly' without fluid dynamic evolution is a trade-off between model accuracy and real-time decision-making efficiency. Incorporating complex Computational Fluid Dynamics (CFD) models would significantly increase the computational load during multi-UAV coordination, making it difficult to meet rapid battlefield response requirements. Future work will explore the integration of semi-empirical diffusion formulas to enhance physical realism while maintaining computational speed. The current model simplifies smoke clouds as uniformly descending spheres, failing to fully account for morphological evolution caused by wind fields and temperature gradients under complex meteorological conditions. Such evolution is closely related to the physical properties of dispersed particles. Furthermore, while simplifying the real target as a point mass (the origin) facilitates the construction of the initial geometric shielding criterion, it may lead to incomplete obscuration when protecting large military assets. Future research will incorporate a 'target envelope space' model to upgrade the shielding criterion from a point-line distance to area/volume projection coverage, ensuring the smoke cloud fully encompasses the physical dimensions of the target to enhance defense reliability. Future research will focus on incorporating fluid dynamics-based irregular smoke dispersion models and exploring the integration of machine learning techniques to pre-generate high-quality initial solutions. This approach aims to enhance real-time scheduling efficiency and system robustness in large-scale dynamic adversarial environments.

Author contributions

Haiyi Wang conceived and designed the overall research framework of multi-UAV smoke decoy deployment strategy. She established the 3D kinematic model and geometric shielding criterion, constructed the objective function and constraint conditions for optimization problems. She implemented the simulated annealing algorithm for single-UAV parameter optimization and the genetic algorithm for multi-UAV cooperative deployment, carried out numerical simulations and data analysis under different scenarios. She also wrote the original draft, revised and polished the full paper, and was responsible for result interpretation and conclusion summarization.

Conflicts of Interest

The authors declare no conflict of interest.

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