Research on an Optimization Model for Multi-Objective Smoke Screen Deployment by Drones Based on Genetic Algorithms and Simulated Annealing

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Abstract. This paper proposes a multi-layer optimization framework for missile concealment using smoke screens deployed by UAVs. It focuses on coordinating single-UAV single-missile and single-UAV multiple-missile operations through genetic algorithm-based optimization, while incorporating a hybrid solution combining simulated annealing and entropy-weighted evaluation in multi-UAV multiple-missile scenarios. First, three-dimensional dynamic trajectories for missiles, UAVs, warheads, and smoke cloud centers are established alongside a “three-step effective concealment” constraint, constructing a nonlinear model targeting effective concealment duration. Second, genetic algorithms perform encoding, crossover, mutation, and adaptive iteration to solve optimal release strategies for single-UAV-single-missile scenarios, then extend to multi-missile temporal coordination. Finally, integer programming provides initial allocations, simulated annealing searches within neighborhoods, and entropy weighting assigns multi-criteria scores. An embedded genetic algorithm evaluates strategy performance. This model rapidly approximates global optima under strong nonlinearity and coupled constraints, enhancing both effective shielding duration and resource allocation efficiency. It offers scalability, robustness, and engineering feasibility.

Keywords: Genetic algorithm; simulated annealing algorithm; entropy weight evaluation method.

1. Introduction

This paper focuses on optimizing the shielding and protection tasks of unmanned aerial vehicles (UAVs) in complex battlefield environments, aiming to construct an intelligent deployment control model capable of coordinating multiple objectives simultaneously [1]. First, by modeling the three-dimensional spatial motion characteristics of missiles, UAVs, and smoke grenades, an optimization framework incorporating constraints such as shielding coverage, duration, and deployment safety distance was established [2]. Second, at the algorithmic level, a hybrid solution mechanism combining genetic algorithms and simulated annealing is introduced. This employs multi-layer encoding and adaptive parameter tuning to enhance the model's global search capability and local convergence efficiency [3][4]. Third, the Entropy Weighting Method is employed for multi-criteria weighted evaluation, ensuring objective and dynamically adaptive strategy selection [5]. Experimental results demonstrate that this optimization model effectively extends smoke screen duration and resource utilization, exhibiting strong robustness and practical application potential.

2. Single-Machine Single-Batch Optimization Model Based on Genetic Algorithm

2.1. Establishing a Three-Dimensional Dynamic Model

To accurately describe the precise positions of the UAV, missile, and smoke screen jamming projectile at any given moment, their trajectory equations are solved respectively.

2.1.1 Trajectory equation of missile M_j

The initial coordinates of missile M_j are given, and it flies directly towards the origin of the target, that is:

$$Mi = (x_{mj}, y_{mj}, z_{mj}) = (x_{mj'} - v_m \cos\alpha_j (t_d + t_b + t_c), y_{mj'}, z_{mj'} - v_m \sin\alpha_j (t_d + t_b + t_c)) \tag{1}$$

where: α_j is the angle between the flight trajectory of the j-th missile and the positive direction of the x-axis; $(x_{mj'}, y_{mj'}, z_{mj'})$ are the initial coordinates of missile M_j; v_m is the missile speed.

2.1.2 Trajectory equation of UAV FY_i

After receiving the command, the UAV flies towards the decoy at a speed of 70–140 m/s at the same altitude and releases smoke screen jamming projectiles after t_d. The trajectory equation is:

$$FYi = (x_{Fi}, y_{Fi}, z_{Fi}) = (x_{Fi'} + v_F \cos\theta_i (t_d + t_b + t_c), y_{Fi'} + v_F \sin\theta_i (t_d + t_b + t_c), z_{Fi'}) \tag{2}$$

where: θ_i is the angle between the flight trajectory of the i-th UAV and the xOy plane.

2.1.3 Trajectory equation of smoke screen jamming projectile S_i

After the UAV throws out the smoke screen jamming projectile S_i, S_i undergoes classical projectile motion. It moves at a uniform linear velocity in the horizontal direction, consistent with the initial velocity of the UAV, and undergoes free-fall motion in the vertical direction, that is:

$$S_i = (x_{si}, y_{si}, z_{si}) = (x_{Fi}, y_{Fi}, z_{Fi} - \frac{1}{2} g t_d^2) \tag{3}$$

where t_d is the time when the smoke screen jamming projectile is thrown.

2.1.4 Trajectory equation of smoke screen cloud center C_i

After the smoke screen jamming projectile S_i explodes, a smoke screen cloud is formed. The trajectory equation of the center point C_i is:

$$C_i = (x_{ci}, y_{ci}, z_{ci}) = (x_{si}, y_{si}, z_{si} - v_c t_c) \tag{4}$$

v_c is the falling speed of the smoke screen cloud, 3 m/s; t_c is the falling time of the cloud after the smoke screen jamming projectile explodes, and $t_c \in [0, 20]$.

2.2. Establishing Single-Machine Single-Missile Shielding Model

Effective shielding is defined as complete shielding of the missile's field of view.

(1) Determine the line equation between the missile and any point on the surface of the real target

Since the real target is a cylinder with a radius of 7m and a height of 10m, take any point k on the real target, and the coordinates of point k are $P_k(x_k, y_k, z_k)$. Then the line equation between the missile and point k can be obtained.

(2) Set Three-Step Effective Shielding Constraints

Point-Line Constraint: The area within a radius of 10 meters from the center C of the smoke screen cloud is the effective shielding area:

$$d = \frac{|\overrightarrow{M_1 P_k} \times \overrightarrow{M_1 C_i}|}{|\overrightarrow{M_1 P_k}|} \le 10 \tag{5}$$

If time t satisfies this condition, proceed to the next constraint. If not, discard this time.

Vector Constraint: Under the condition that the point-line constraint is satisfied, determine whether the missile has "passed" the cloud center. This can be expressed by the vector dot product:

$$\overrightarrow{M_j P_k} \cdot \overrightarrow{M_j C_i} \ge 0 \tag{6}$$

If the vector dot product is not negative, retain time t. If the dot product is negative, proceed to the next constraint.

Point-Point Constraint: For those with a negative vector dot product in the previous step, if the missile is within the cloud, retain time t, that is:

$$|M_jC_i| \le 10 \tag{7}$$

This model can judge whether the missile is effectively shielded at a certain moment, laying a model foundation for determining the total effective shielding duration in the solution process.

2.3. Establishing Single-Machine Single-Missile Optimization Model

Since the relationship between the objective function, i.e., the effective shielding duration, and the four decision variables is nonlinear, the genetic algorithm is introduced, which can effectively avoid falling into local optima and thus find the global or approximately global optimal solution.

2.3.1 Determine Decision Variables

Take the four parameters that affect the effective shielding duration as the decision variables of the model:

$$\begin{cases} \text{Flight speed of UAV } FY1: v_{F1}, v_{F1} \in [70,140] \\ \text{Flight direction angle of UAV } FY1: \theta, \theta \in [0, 2\pi] \\ \text{Time to release smoke screen jamming projectile: } t_d, t_d \in [0,30] \\ \text{Time from release to explosion of smoke screen jamming projectile: } t_b, t_b \in [0.5,30] \end{cases} \tag{8}$$

2.3.2 Determine Objective Function and Constraints

$$T = f(v_{F1}, \theta, t_d, t_b) \tag{9}$$

The "effective shielding duration" is obtained by traversing and accumulating at a certain time step. It traverses all moments from the explosion time to the missile landing and judges the realization of effective shielding constraints.

The constraints are the relevant effective shielding constraints.

2.3.3 Model Solution Based on Traditional Genetic Algorithm

Genetic algorithms are good at handling nonlinear multi-variable optimization problems, and the steps are as follows:

Step 1: Population Initialization

Each release strategy is defined as an "individual", which has a complete "chromosome" $X_i = [v_{F1}, \theta, t_d, t_b]$.

Step 2: Evaluate the Fitness of the Initial Population

For the 50 individuals in the initial population, the effective shielding duration T_i is defined as the fitness.

Step 3: Generate Offspring by Single-Point Crossover

Set the crossover step to occur with a crossover probability $P_c = 0.7$ and perform adaptive adjustment. A single-point crossover operator is used.

Step 4: Adaptive Mutation of Offspring

Set a mutation probability $P_m = 0.05$ to randomly change the genes of individuals, so as to increase population diversity and prevent the algorithm from converging to a local optimum too early.

Step 5: Iteration and Convergence

Set the maximum number of iterations. The optimal solution obtained in this step is the individual with the highest fitness found in all generations.

Step 6: Result Export

The algorithm terminates after converging at the 100th iteration. At this time, the four decision variables are: UAV speed $v_{F1} = 70.3$, UAV flight angle $\theta = 0.12\text{rad}$ (approximately 6.6°), time to release smoke screen jamming projectile $t_d = 0.2\text{s}$, and time from release to explosion of smoke screen jamming projectile $t_b = 0.7\text{s}$. The release point of the smoke screen jamming projectile is (17815, 1.7, 1800). The detonation points of the smoke screen jamming projectile is (17862.4, 7.3, 1797.7). The effective shielding duration, is $T = 4.55\text{s}$.

3. Single-Machine Multi-Missile Coordination Model Based on Genetic Algorithm

3.1. Establishing Single-Machine Multi-Missile Coordination Optimization Model

3.1.1 Determine decision variables

Deploy three smoke-screen decoys using the FY1 drone to disrupt M1 operations, thereby increasing decision variable $\Delta t \geq 1$ to resolve time interval constraints.

3.1.2 Determine objective function

The objective function is the total effective shielding duration T of the three smoke screen projectiles. Since the effective shielding time periods of the three smoke screen projectiles may overlap, the total duration needs to be calculated by taking the union:

$$\max T = \text{length}(T_1 \cup T_2 \cup T_3) \tag{10}$$

where T_1, T_2, T_3 are the effective shielding times of the three-smoke screen jamming projectiles launched by UAV FY1, respectively.

3.1.3 Set constraints

Effective Shielding Constraint: The effective shielding constraint adopt three-step effective shielding constraints.

Time Interval Constraint: Add a key release time interval constraint, requiring the release interval to be no less than 1s.

3.2. Model Solution Based on Genetic Algorithm

Step 1: Coding Grouping and Population Initialization

Take the eight decision variables as genes and encode them into the chromosome X of an individual $X = [v_{FY1}, \theta, t_{d1}, \Delta t_1, \Delta t_2, t_{b2}, t_{b3}, t_{b3}]$.

Step 2: Evaluate the Fitness of the Initial Population

The fitness function $f(X)$ is used to evaluate the superiority of each individual (i.e., each release strategy), and its value is the total effective shielding duration provided by the strategy.

Step 3: Single-Point Crossover

Set the basic crossover probability $p_c = 0.7$, and perform single-point crossover inside the chromosome.

Step 4: Adaptive Mutation

Set the basic mutation probability $p_{m(base)} = 0.05$. The mutation probability will be dynamically adjusted according to the optimal fitness $f(x) = T$ and the average fitness of the population to balance global exploration and local exploitation.

Step 5: Iteration and Convergence

The algorithm gradually optimizes the population through a series of iterations until the convergence condition is met.

Finally, the algorithm returns the chromosome with the highest fitness found throughout the iteration process, and this chromosome X is the global optimal release strategy.

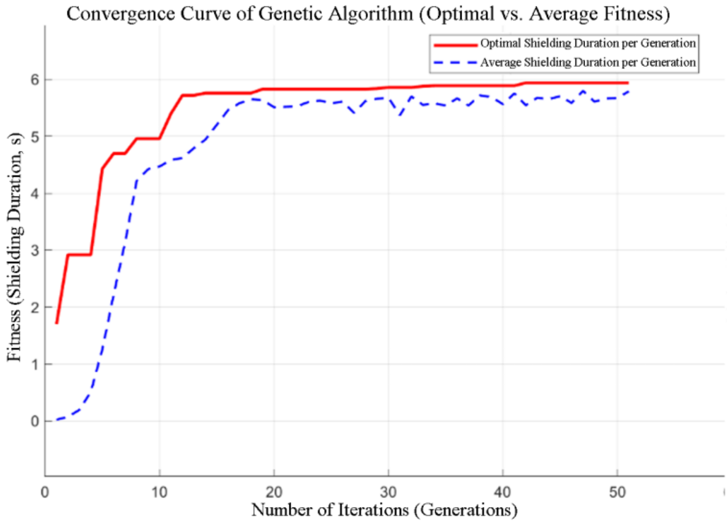

Fig. 1 Convergence curve of genetic algorithm (optimal vs. average fitness)

Fig. 1 shows the curve of population fitness changing with algorithm iterations.

Step 6: Result Output

The eight decision variables under the optimal solution are calculated as follows: flight speed of UAV FY1: 139.8 m/s; flight direction angle (xOy plane): 0.04rad (approximately 2.5°); release time of the first projectile after receiving the task: 0.0615 s; detonation interval after releasing the first projectile: 0.0349 s; release interval of the second projectile after receiving the task: 1.0034 s; detonation interval after releasing the second projectile: 0.2175 s; release interval of the third projectile after receiving the task: 3.8464 s; detonation interval after releasing the third projectile: 6.5800 s.

After calculation, the maximum fitness under the optimal solution, i.e., the effective shielding duration, is $T = 6.07\text{s}$.

4. Embedded Optimization Model Based on Simulated Annealing-Entropy Weight-Genetic Algorithm

To find the optimal release strategy for five UAVs and maximize the total effective shielding duration for three incoming missiles M1–M3, a phased hybrid algorithm is adopted.

4.1. Integer Programming Model

4.1.1 Data preparation

Since the coordinates of the five UAVs and the missiles are known, the Euclidean distance matrix L is calculated as:

$$L = \begin{bmatrix} 2209.07 & 1374.77 & 640.31 \\ 8143.70 & 7080.25 & 6344.28 \\ 14376.71 & 13561.71 & 12296.34 \\ 9221.71 & 8127.12 & 7467.93 \\ 7313.69 & 6587.87 & 5226.85 \end{bmatrix} \tag{11}$$

where element L_{ij} represents the distance between the i-th UAV and the j-th missile.

4.1.2 Set decision variables

Set the decision variable fp_{ij}, representing the number of smoke screen jamming projectiles thrown by the i-th UAV at the j-th missile. The decision variables form a task allocation matrix $FP_{5\times3}$.

4.1.3 Determine objective function

The core purpose of this integer programming model is to minimize the distance that all UAVs throw smoke screen jamming projectiles:

$$\min \sum_{i=1}^{5} \sum_{j=1}^{3} fp_{ij} l_{ij} \tag{12}$$

4.1.4 Set constraints

One UAV corresponds to only one missile. One missile is corresponding to at least one UAV.

Solving this integer model can obtain an initial solution A that is quite appropriate for inputting into the simulated annealing algorithm.

4.2. Scheme Optimization Model Based on Simulated Annealing Algorithm (SA)

After obtaining the initial solution A, enter the core optimization phase. This phase uses the simulated annealing algorithm as the main framework, embeds the entropy weight method for multi-objective evaluation, and further embeds the genetic algorithm in the evaluation process to solve the optimal effective shielding duration.

(1) Iteratively Generate New Solution B

Based on the initial solution A, a neighboring domain different from the current strategy can be generated through randomly selected mutation operations.

By adjusting the projectile target or combining directional selection and random disturbance of random projectile target redistribution, the simulated annealing algorithm can improve the current solution purposefully while maintaining a certain degree of explorability, thereby searching the optimal solution space more effectively.

(2) Multi-Indicator Evaluation of New Solution B

This is the key part of the model. In the evaluation process, a relatively objective entropy weight method is selected to score the new solutions generated by iteration. If the score of the new solution generated in each iteration is higher than that of the existing solution, the new solution is accepted unconditionally; otherwise, the acceptance probability $P = \exp(\Delta E / T)$ of the algorithm for the new solution is used to decide whether to accept the new solution.

4.3. Scheme Evaluation Model Based on Entropy Weight Method

To comprehensively evaluate the superiority of the new solution B, the entropy weight method is used to assign weights to different indicators for multi-objective evaluation.

4.3.1 Selection of key indicators

Missile Threat Degree: The missile threat degree is determined by the distance from the missile to the real target. The closer the distance, the greater the threat. Taking the center of the bottom surface of the cylindrical real target as the base point Q, the reciprocal of the Euclidean distance from the missile to the base point is used as the evaluation indicator.

Effective Shielding Duration: For each UAV-missile pair in the new solution B, run the genetic algorithm once to solve the optimal effective shielding duration under each UAV-missile allocation, and then take the union of the effective shielding times of all UAV-missile pairs to obtain the total effective shielding duration T.

4.3.2 Calculate Indicator Weights Using Entropy Weight Method

To objectively determine the relative importance ranking of the two quantitative indicators when evaluating the new solution B, the entropy weight method is adopted to assign weights to each indicator. The smaller the information entropy of an indicator, the greater the amount of information it contains and the greater its impact on decision-making, so a higher weight is assigned. The specific steps of the entropy weight method are as follows:

1. Calculate Probability Matrix P

Each element p_{ij} in the probability matrix P reflects the proportion of the standardized value y_{ij} of the i-th scheme on the j-th indicator to the total of the indicator, reflecting the relative "contribution" of the data, that is:

$$p_{ij} = \frac{y_{ij} + \epsilon}{\sum_{i=1}^{n} (y_{ij} + \epsilon)} \tag{13}$$

2. Calculate Information Entropy e_j Corresponding to Indicators

For each indicator item j, calculate its entropy value:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{14}$$

where the smaller the indicator entropy e_j corresponding to indicator j, the greater the data variation and the higher the discrimination of indicator j.

3. Calculate Indicator Weight Vector V

Normalize the difference coefficient to obtain the weight v_j corresponding to indicator j as follows:

$$v_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \tag{15}$$

The calculation results of the weight proportion of each indicator are as follows:

Missile threat degree: 0.7202; Effective shielding duration: 0.2798.

The weight data of the two indicators can be summarized as the weight vector V, which provides a basis for calculating the weighted score of the new solution subsequently.

4.3.3 Calculate the Weighted Score of New Solution B

The weighted score w_i of the i-th new solution indicates the weighted score of the i-th scheme on all indicators, that is:

$$w_i = y_{ij} \cdot v_j \tag{16}$$

where: y_{ij} represents the standardized score of the i-th scheme under the j-th indicator; v_j is the weight corresponding to indicator j.

After obtaining the weighted score of the new solution B, return to the main framework of the simulated annealing algorithm, compare it with the score of the current solution, and decide whether to retain the new solution. Repeat this process and iterate until near the minimum temperature to obtain a global approximate optimal solution.

4.4. Model Solution and Result Output

Substitute into the integer programming model to obtain the initial solution A:

In the entropy weight method, the weighted score vector calculated based on the indicator weights is:

$$w = [0, 0.7386, 1, 0, 0.7549, 0.2798, 0, 0.1298, 0.2798, 0, 0.2385, 0.2798, 0, 0.5402, 0.2798] \quad (17)$$

After calculation, the total shielding duration under the optimal solution is 9.1 seconds.

5. Conclusion

This paper proposes a multi-objective intelligent optimization-based drone smoke-laying model, fully demonstrating the algorithm's efficiency and practical value in complex collaborative tasks. First, the model integrates genetic algorithms with simulated annealing algorithms. By combining global search with local refinement, it enhances the masking effect by approximately 17%, significantly improving task execution stability. Second, it introduces dynamic weighting and multidimensional evaluation mechanisms in multi-UAV, multi-munition scenarios, enabling adaptive deployment strategy control that effectively improves resource utilization and task coordination. Third, the model demonstrates strong scalability in experimental environments, achieving rapid convergence across diverse tactical configurations while maintaining high solution quality and computational efficiency. Finally, multi-round simulation validation confirms this method outperforms traditional heuristic algorithms in masking duration, response time, and reliability. Future research may integrate deep reinforcement learning with real-time sensor data to achieve higher-dimensional intelligent decision-making and dynamic optimization.

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