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MULTI-AGENT COORDINATION AND RESOURCE ALLOCATION OPTIMIZATION STRATEGIES FOR SMOKE SCREEN DEPLOYMENT AGAINST DYNAMIC TARGETS

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Abstract: This paper investigates optimal defense strategies for countering single or multiple high-speed incoming missiles by deploying smoke screen decoys through coordinated operations of multiple unmanned aerial vehicles (UAVs) in complex dynamic battlefield environments. The research focuses on the challenging problem of multi-agent cooperative defense and large-scale resource allocation. First, for a three-UAV, single-decoys cooperative countermeasure strategy, a joint optimization model incorporating parameters such as UAV flight direction, velocity, deployment timing, and detonation timing is constructed. A differential evolution algorithm is employed to solve this high-dimensional combinatorial optimization problem. Through iterative differential evolution, optimal parameter configurations for the three UAVs are obtained, achieving effective shielding against missile M1. Subsequently, the scenario is expanded to the most complex five-UAV, three-missile integrated defense problem. This problem involves multiple UAVs, multiple missiles, multiple missile deployments, and resource allocation, constituting a typical large-scale combinatorial optimization problem. This paper innovatively proposes a two-layer hybrid optimization framework combining the Hungarian algorithm and genetic algorithm. The upper layer utilizes the Hungarian algorithm to determine the optimal task allocation between missiles and UAVs, minimizing the initial distance cost to ensure optimal spatial separation. The lower layer, with fixed allocations, employs a genetic algorithm to refine the deployment parameters for each UAV. The final optimized solution successfully achieves comprehensive interference against three missiles, demonstrating the dual-layer model's capability to obtain near-global-optimal multi-objective defense strategies while ensuring real-time feasibility.
Keywords: Spatial coordinate system; Kinematic model; Genetic algorithm

1 INTRODUCTION

Smoke-based jamming technology has found extensive application in modern military operations. Its core value lies in generating smoke clouds to create a protective screen in front of targets, effectively obscuring enemy missile detection systems and safeguarding genuine objectives. In practical applications, existing long-endurance UAVs equipped with smoke countermeasure munitions must instantly adjust flight states and deployment strategies (e.g., flight direction, velocity, release point, detonation point) upon detecting missiles to maximize the effective shielding duration of smoke clouds over the true target[1-2]. This challenge raises two core technical questions: First, how to precisely calculate the effective shielding duration of a single smoke decoy against a dynamic real target, given known motion states and initial parameters of the missile, UAV, and smoke decoy. Second, how to determine the single-resource jamming strategy that maximizes the real target's complete shielding duration by optimizing strategic parameters such as the UAV's flight direction, speed, and the smoke decoy's deployment and detonation timing. Previous studies addressing the masking effects of complex dynamic targets often relied excessively on simplified geometric models or coarse time steps, failing to provide precise calculations meeting high-precision engineering requirements[3]. The primary innovations of this research are: First, establishing spatial dynamic models for missiles, UAVs, and smoke grenades, laying the foundation for precise calculations. Second, it achieves high-precision determination of smoke-induced complete concealment by discretely sampling the target's cylindrical surface and applying geometric discriminants for line-sphere intersections. Most critically, addressing the multivariate nonlinear optimization problem of maximizing concealment duration, this section introduces a genetic algorithm for global optimization. This algorithm logically integrates complex kinematic models and geometric criteria without simplification, thereby identifying the optimal single-resource deployment strategy. The research approach comprises two steps: First, constructing spatial and geometric determination models to precisely calculate concealment duration under given parameters; Second, using this duration as the objective function, the genetic algorithm searches the strategy parameter space for the optimal combination[4-5].

2 DIFFERENTIAL EVOLUTION OPTIMIZATION FOR MULTI-UAV COOPERATIVE DEFENSE

2.1 Model Establishment

This part requires using three UAVs (FY1, FY2, FY3), each deploying one smoke interference bomb, to interfere with missile M1. This section will detail how to establish a mathematical model to solve this problem.
Model Constraints

Deployment time constraint: The time interval between smoke interference bombs deployed by each UAV must be at least 1 second:

$$t_{j(k+1),p} \geq t_{jk,p} + 1, \forall j, k \quad (1)$$

Detonation time constraint: The detonation time shall not be earlier than 1 second after deployment:

$$t_{jk,b} \geq t_{jk,p} + 1, \forall j, k \quad (2)$$

Speed and direction constraints: The UAV's speed and direction angle must be within the allowable range:

$$v_j \in [70,140], \forall j \quad (3)$$

$$\theta_j \in [0,2\pi), \forall j \quad (4)$$

Resource allocation constraint: Each UAV can deploy at most one smoke interference bomb:

$$\sum_m x_{jkm} \leq 1, \forall j, k \quad (5)$$

where x_{jkm} is the smoke bomb allocation indicator variable, $x_{jkm} \in \{0,1\}$, indicating whether smoke bomb k is used to interfere with missile m.
Smoke bomb allocation constraint: Each smoke bomb can only be allocated to one target:

$$\sum_k x_{jkm} \leq 1, \forall j, m \quad (6)$$

Objective Function
Maximize the total effective shielding time:

$$\max \sum_{j=1}^{3} \sum_{k=1}^{K_j} T_{c,jk} \quad (7)$$

where $K_j = 1$ is the number of smoke bombs deployed by UAV j, and $T_{c,jk}$ is the effective shielding time of the k-th smoke bomb deployed by the j-th UAV.

2.2 Solution Model

The Differential Evolution (DE) algorithm is used to solve this optimization problem. The differential evolution algorithm is a population-based optimization algorithm suitable for global optimization problems in continuous spaces[6]. It gradually approaches the optimal solution through mutation, crossover, and selection operations during iterations. Randomly generate a set of UAV flight speeds, direction angles, deployment times, and detonation times as the initial population. Each individual consists of four parameters: flight speed v_j, direction angle θ_j, deployment time $t_{d,j}$, and detonation time $t_{b,j}$. Calculate the total effective shielding time for each individual. The fitness function is the total effective shielding time, with the goal of maximizing this value. Perform mutation operation on each individual to generate a mutation vector. The mutation vector is generated based on the difference between the current individual and two other randomly selected individuals[7-8]. Perform crossover operation between the mutation vector and the current individual to generate a trial vector. The crossover operation randomly selects corresponding parameters from the mutation vector and the current individual for combination.
The algorithm compares the fitness of the trial vector and the current individual. If the fitness of the trial vector is better than that of the current individual, the trial vector replaces the current individual[9-10]. Repeat steps 3-5 until the preset number of iterations is reached or the convergence condition is satisfied. During the solution process, the UAV flight parameters are first discretized to adapt to the search space of the differential evolution algorithm. The specific parameter ranges are as follows:
Flight speed: $v_j \in [70,140]$ m/s
Flight direction angle: $\theta_j \in [0,2\pi)$
Deployment time: $t_{j,p} \geq 0$
Detonation time: $t_{j,b} \geq t_{j,p} + 1$
Through iterative optimization of the differential evolution algorithm, three sets of solutions meeting the conditions are found, each corresponding to the optimal flight parameters of one UAV. The specific solutions are as follows:
Solution 1: $i = 44, j = 118, q = 5, s = 7$, Result = 4.1 seconds
Solution 2: $i = 43, j = 80, q = 12, s = 7$, Result = 3.35 seconds
Solution 3: $i = 49, j = 98, q = 8, s = 6$, Result = 0.72 seconds

2.3 Analysis of Problem 4 Results

The differential evolution algorithm calculates three sets of solutions meeting the conditions, each corresponding to the flight parameters and deployment strategy of one UAV. These solutions maximize the effective shielding time for missile M1 while satisfying all constraints. The specific results are as follows: Flight direction angle: 252.10°; Flight speed: 118 m/s; Deployment point coordinates: (11818.67, 838.55, 1400) m; Detonation point coordinates: (11564.82, 52.53, 1159.9) m; Effective shielding time: 4.1 seconds; Flight direction angle: 246.37 °; Flight speed: 80 m/s; Deployment point coordinates: (11615.23, 520.48, 1400) m; Detonation point coordinates: (11390.79, 7.43, 1159.9) m;

Effective shielding time: 3.35 seconds; Flight direction angle: 280.75 ° ; Flight speed: 98 m/s; Deployment point coordinates: (12146.23, 629.76, 1400) m; Detonation point coordinates: (12255.89, 52.08, 1223.6) m; Effective shielding time: 0.72 seconds.
From the results, it can be seen that the deployment strategy of FY1 provides the longest effective shielding time of 4.1 seconds, indicating that under the given conditions, the smoke bomb can more effectively cover the flight path of missile M1. FY2 also performs well, providing a shielding time of 3.35 seconds. However, the shielding time of FY3 is relatively short, only 0.72 seconds, which may be due to the poor selection of its deployment and detonation points, resulting in the smoke cloud failing to provide sufficient shielding during the critical phase when the missile approaches the real target. Through visualization results, we can see the flight trajectory of each UAV, the deployment and detonation positions of the smoke bombs, and the effective shielding effect on missile M1. The graphs show that the smoke bombs of FY1 and FY2 successfully form effective shielding when the missile approaches the decoy target, while the smoke bomb of FY3 also forms shielding but is less effective than the previous two. The strategy of collaborative deployment of smoke interference bombs by three UAVs is successfully obtained through the differential evolution algorithm to maximize the effective shielding time for missile M1. The results show that by optimizing the flight parameters and deployment strategy of UAVs, continuous and effective interference can be provided during the missile's approach phase.

3 A TWO-LAYER OPTIMIZATION FRAMEWORK FOR MULTI-AIRCRAFT MULTI-WEAPON MISSION ALLOCATION

3.1 Model Establishment

This part requires using 5 UAVs (each with a maximum of 3 smoke bombs) to simultaneously interfere with 3 missiles (M1, M2, M3). Compared with the previous four problems, this problem introduces multiple UAVs, multiple missiles, multiple bomb deployments, and resource allocation, making it a typical large-scale combinatorial optimization problem.
On the basis of the single-UAV/multi-UAV modeling in Problems 3 and 4, we establish a two-layer structure of "UAV-missile allocation" and "multi-bomb deployment optimization": the upper layer matches 3 missiles with 5 UAVs (ensuring optimal spatial distance); the lower layer optimizes the deployment parameters (course, speed, deployment time, detonation delay) of each UAV; the overall goal is to maximize the total shielding time of the three missiles when approaching the real target.
Decision Variables
$\{\theta_i, v_i, t_{i,j,p}, t_{i,j,b}, x_{j,k,m}\}$, where $x_{j,k,m} \in \{0,1\}$ is the assignment variable, indicating whether the j-th smoke bomb of UAV i is used to interfere with missile m.
Constraints
Deployment time interval: Smoke bombs continuously deployed by the same UAV must satisfy $\Delta t \geq 1$ second.
Speed/direction constraints: $70 \leq v_i \leq 140$, $\theta_i \in [0,2\pi)$.
Resource constraint: Each UAV can carry at most 3 bombs.
Allocation constraint: Each bomb can only be assigned to one missile.
Objective Function

$$\max \mathscr{L} = \sum_{m=1}^{3} \sum_{i=1}^{5} \sum_{j=1}^{3} x_{j,k,m} \cdot T_{i,j,m} \tag{8}$$

where $T_{i,j,m}$ represents the effective shielding time of the j-th smoke bomb of UAV i on missile m.
This model inherits the geometric shielding determination method (missile-real target-cloud cluster relationship) from Problems 1 to 4. However, due to the superposition of multiple targets and multiple resources, the problem exhibits exponential complexity and requires heuristic intelligent algorithms for solution.

3.2 Model Solution

We adopt a two-layer hybrid optimization framework of "Hungarian algorithm + Genetic Algorithm (GA)". The upper layer (task allocation) uses the Hungarian algorithm to solve the optimal matching problem between 3 missiles and 5 UAVs. The cost matrix takes the minimum distance from the initial position of the UAV to the missile's flight path to ensure that UAVs are preferentially allocated to missiles that are easier to interfere with spatially. For the remaining 2 UAVs, the "nearest path distance" criterion is used for auxiliary allocation. The lower layer (deployment parameter optimization) calls the genetic algorithm GA to optimize the deployment plan of a single UAV under fixed task allocation.
Chromosome Encoding
$[\theta, v, q_1, s_1, q_2, s_2, q_3, s_3]$, a total of 8 continuous variables, corresponding to the course, speed, and deployment time and delay of 3 bombs respectively. Feasibility checks are also performed; individuals with a deployment interval of less than 1 second are directly judged as invalid, and their fitness is set to zero.
Fitness Function

Call eval_cover_time() to return the total shielding time.
Genetic Operators
Roulette selection, single-point crossover, and multi-point mutation with a probability of 0.25.
Algorithm Parameters
Population size: 100, number of iterations: 100, crossover probability: 0.7.

3.3 Result Analysis

After optimization, the task allocation is as follows: FY1→M1, FY2→M2, FY3→M3, FY4→M2, FY5→M3. For each UAV, the optimal flight and deployment parameters are obtained through optimization (sorted by fitness).
The operation results show that after genetic algorithm optimization, all 5 UAVs (FY1－FY5) obtain clear flight direction angles, flight speeds, as well as the deployment coordinates, detonation coordinates, and corresponding effective shielding times of 3 smoke bombs.
FY1−FY2−FY5 (allocated to M1, M2, M3): The overall shielding times are approximately 9.29 s, 4.06 s, and 2.28 s respectively, indicating that the three UAVs allocated in the early stage play a major protective role.
FY3 and FY4 provide supplementary protection for M3 and M2 respectively, increasing the effective shielding time by 1.58 s and 3.17 s.
From the single-UAV results, in most cases, the first interference bomb contributes the longest shielding time (e.g., the first bomb of FY1 has an effective duration of up to 4.28 s), while the third bomb often has a shielding time close to 0 s, indicating that the available window shortens as the missile gradually approaches the target.

4 CONCLUSIONS

This section successfully establishes an accurate calculation model for effective smoke screen duration and utilizes a genetic algorithm to optimize the single-resource interference strategy. For duration estimation, we constructed a spatial scenario involving missiles, UAVs, smoke grenades, and real targets, establishing dynamic models for each entity. Through discrete sampling of the target surface and geometric criteria for segment-sphere intersections, we precisely calculated the complete effective concealment duration of 1.39 seconds under a given deployment strategy. For strategy optimization, we constructed an optimization model with UAV flight parameters and smoke grenade timing parameters as decision variables to maximize effective concealment duration. This model employs a genetic algorithm for global optimization, ultimately achieving a maximum effective concealment duration of 4.51 seconds, significantly enhancing single-resource deployment performance.
This study retains certain limitations in modeling and solution processes. Model construction incorporates simplifying assumptions, such as assuming all entities move without resistance. Additionally, we assumed that after detonation, the smoke-screen interference projectile maintains a constant spherical shape with unchanging radius throughout its effective interference duration, disregarding other factors that could distort its shape. Furthermore, the true target was modeled as a regular cylinder, neglecting the possibility of irregular structures encountered in practice. Future research should focus on enhancing the model's engineering applicability and accuracy. Exploring the incorporation of environmental drag terms into the dynamic model and developing more sophisticated smoke cloud shape models could improve prediction accuracy. To address the limitation where genetic algorithms may converge to similar parameters in later iterations, making it difficult to find solutions superior to existing ones, future work could investigate combining other optimization algorithms or refining inertial weights. This would further enhance the global optimization capability for finding optimal strategies in complex, multi-variable scenarios.

COMPETING INTERESTS

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

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