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Research on Precise Determination of Dynamic Target Indicators and Optimal Resource Allocation Strategies Based on Binary Search and Genetic Algorithms

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Abstract: This study addresses the challenges of precisely determining dynamic target indicators and optimizing single-resource allocation strategies. For effective coverage of cylindrical targets by resources within a specific airspace, we first establish the kinematic equations governing the motion of missiles, resource carriers, and deployed resources. To accurately calculate effective engagement duration, we construct a cylindrical occlusion indicator function, which determines occlusion status based on the minimum distance between the line-of-sight and the center of the resource cloud. To enhance computational accuracy and overcome limitations of traditional time-scanning methods, this study innovatively employs a binary search algorithm to precisely locate discontinuity points where the occlusion indicator function value jumps, thereby accurately calculating the effective duration of resource-target occlusion. Building upon this foundation, a nonlinear single-objective optimization model was developed. This model uses the UAV's heading angle, velocity, deployment time, and fuse delay as decision variables, with the objective of maximizing the total effective coverage duration. The optimization model was solved using a genetic algorithm simulating biological evolution, yielding optimal resource deployment parameter combinations that significantly enhance resource allocation performance.

Keywords: Optimization model, Binary search method, Genetic algorithm.

1. Introduction

In complex dynamic environments such as modern air defense operations, rapidly deploying resources while maximizing their effective interference duration against high-precision targets presents a core challenge. The current context involves high-velocity threats requiring low-cost resources—such as smoke-generating decoys—to form obscuring clouds within specific airspace. Consequently, there is an urgent need to establish precise mathematical models for predicting the dynamic interaction between resource trajectories and target paths, thereby determining optimal deployment strategies [1].

The central research question addressed in this section is: How can we precisely calculate the effective duration of effect for a single-deployment resource on a cylindrical target under given kinematic conditions? Furthermore, how can we optimize the flight parameters of the resource carrier and the deployment timing parameters to maximize this duration? Previous studies addressing precise criteria for complete cylindrical concealment often relied on point target approximations or insufficient refinement after geometric acceleration, resulting in inadequate accuracy for determining concealment start and end times [2].

The innovations in this section are: 1. Establishing a comprehensive kinematic model encompassing missiles, UAVs, and smoke-screen decoys. 2. Developing point-target occlusion indicator functions and cylindrical full-occlusion indicator functions, achieving precise calculation of effective occlusion duration through a binary search method, significantly enhancing computational robustness. 3. Developed a nonlinear optimization model using UAV attitude and deployment timing as decision variables to maximize occlusion duration, efficiently solving it via genetic algorithms to obtain globally optimal or near-optimal deployment strategies [3, 4].

This section's research approach comprises two primary steps: First, establishing the occlusion indicator function through kinematic models and geometric criteria, then determining precise effective duration using the bisection method. Second, constructing a single-objective optimization model with this duration as the objective function, incorporating constraints on UAV altitude and effective evaluation windows, and employing a genetic algorithm to search for optimal combinations of heading angle, velocity, deployment timing, and fuse delay.

2. Calculation Model for Effective Concealment Duration of Single Smoke Grenades on Cylindrical Targets

2.1. Model Establishment

(1) Kinematic Model

Missiles move in a straight line at a constant speed, always pointing to the decoy target located at the coordinate origin $(0,0,0)$. Let the initial position of the missile be M_0. The unit direction vector pointing to the decoy target is defined as:

$$u_M = \frac{-M_0}{\|M_0\|} \tag{1}$$

Where M_0 represents the position vector of the decoy target, and $\|M_0\|$ represents the modulus of the vector.

Given the missile flight speed $v_M = 300$ m/s, the position of the missile at time t is derived from the displacement formula of uniform straight-line motion combined with the unit direction vector:

$$M(t) = M_0 + v_M \cdot u_M \cdot t \tag{2}$$

UAVs fly at a constant altitude in a straight line toward the decoy target. To determine their flight direction, the unit pointing vector is defined as:

$$u_U = \frac{-U_0}{\|U_0\|} \tag{3}$$

Where U_0 is the initial position vector of the UAV, and $\|U_0\|$ is the modulus of the vector.

Given the UAV flight speed $v_U = 120$ m/s, the position of the UAV at time t is obtained from the displacement formula of uniform straight-line motion:

$$U(t) = U_0 + v_U \cdot u_U \cdot t \tag{4}$$

Let the release time of the interference bomb be t_{rel} and the detonation time be t_{exp} ($t_{exp} = t_{rel} + \tau$, where τ is the fuze delay).

At the moment of release, the position and horizontal speed of the interference bomb are respectively:

$$P_{rel} = U(t_{rel}) \tag{5}$$

$$v_{rel} = v_U \cdot u_U \tag{6}$$

Ignoring air resistance, the interference bomb performs projectile motion after release, and its position at time t ($t \in [t_{rel}, t_{exp}]$) is calculated as:

$$P_{bomb}(t) = P_{rel} + v_{rel} \cdot (t - t_{rel}) + \frac{1}{2} g \cdot (t - t_{rel})^2 \cdot e_z \tag{7}$$

Where e_z is the unit vector in the vertical direction.

At the moment of detonation, the center position of the smoke cloud cluster is the position of the interference bomb at the detonation time:

$$C_0 = P_{bomb}(t_{exp}) \tag{8}$$

After detonation, the center of the smoke cloud cluster sinks at a constant speed of $v_s = 3$ m/s, and its position at time t ($t \geq t_{exp}$) is:

$$C(t) = C_0 - v_s \cdot (t - t_{exp}) \cdot e_z \tag{9}$$

(2) Criterion for Rationality of Point Target Approximation

In the analysis of smoke shielding for cylindrical targets, direct handling of geometric shielding of the cylinder is complex, so the point target approximation method can be adopted first. The core idea is: if within the effective shielding interval, the "angular scale" of the cylinder is much smaller than the "angular coverage" of the smoke sphere from the missile's viewpoint, it is reasonable to use point T_0 to represent the cylinder for geometric shielding determination with controllable numerical errors.

From the missile's perspective, the angular radius of the real target is calculated as:

$$\alpha_T = \arctan\left(\frac{r_T}{d_{MT}(t)}\right) \tag{10}$$

Where r_T is the radius of the cylinder, and $d_{MT}(t)$ is the distance from the missile position to the representative point of the cylinder. The introduction of small-angle approximation ($\sin\alpha \approx \tan\alpha \approx \alpha$ when α is very small) greatly simplifies subsequent calculations, and the error is negligible when the angular scale is small.

The upper bound of the angular radius of the smoke sphere from the missile's viewpoint represents the "angular coverage range" of the smoke sphere relative to the missile's perspective, calculated as:

$$\alpha_S = \arcsin\left(\frac{R_S}{d_{MC}(t)}\right) \tag{11}$$

Where $d_{MC}(t)$ is the distance from the missile position to the center of the smoke sphere, and R_S is the effective radius of the smoke sphere.

If the missile's line of sight (central ray) is tangent to or intersects the smoke sphere, the actual axial angular deviation $\delta(t)$ satisfies:

$$\delta(t) = \arccos\left(\frac{(T_0 - M(t)) \cdot (C(t) - M(t))}{\|T_0 - M(t)\| \cdot \|C(t) - M(t)\|}\right) \tag{12}$$

At the point of tangency (the line of sight is tangent to the smoke sphere), $\delta(t) + \alpha_T = \alpha_S$.

In terms of angles, if the following condition is met:

$$\delta(t) + \alpha_T \leq \alpha_S \tag{13}$$

Then all lines of sight from the missile's viewpoint to the cylinder pass through the smoke sphere (and the intersection points are in front of the target), i.e., "complete cylinder shielding" is achieved.

(3) Shielding Criterion for Point Targets

To judge the shielding effect of smoke on the missile pointing to the point target, a shielding indicator function including two cases—"missile inside the smoke" and "line of sight passing through the smoke"—is constructed to determine the shielding duration through quantitative calculation.

Based on the rationality criterion of point target approximation, only one point on the cylinder boundary is initially selected as the point target T. For any time t, the line-of-sight segment from the missile to this point is:

$$L(t, s) = M(t) + s(T - M(t)), s \in [0,1] \tag{14}$$

Where s is the segment parameter, representing the range of the segment from the missile position to the point target.

Taking the union of "missile inside the smoke" and "line of sight passing through the smoke", the shielding indicator function for the point target is defined as:

$$\chi_T(t) = \mathbb{I}(\|M(t) - C(t)\| \leq R_S \text{ or } d_{MC}(t) \leq R_S) \tag{15}$$

Where $\mathbb{I}(\cdot)$ is the indicator function, taking 1 if the condition is satisfied and 0 otherwise; $d_{MC}(t)$ is the minimum distance from the center of the smoke cloud cluster to the line-of-sight segment.

To calculate $d_{MC}(t)$, the following variables and formulas are introduced:

Let $A = M(t)$, $B = T$, $P = C(t)$. The squared modulus of vector $\overrightarrow{AB}$ is $|\overrightarrow{AB}|^2 = (B - A) \cdot (B - A)$. The projected value of the segment parameter s is calculated as:

$$s_0 = \frac{(P - A) \cdot (B - A)}{|\overrightarrow{AB}|^2} \tag{16}$$

$$s_{clip} = \max(0, \min(1, s_0)) \tag{17}$$

Where the clip function restricts s_0 to the range [0, 1] to ensure it corresponds to a point on the segment.

The minimum distance from the line-of-sight segment to the center of the smoke sphere is:

$$d_{MC}(t) = \|P - (A + s_{clip} \cdot (B - A))\| \tag{18}$$

The boundary between shielding and non-shielding is given by the univariate equation:

$$d_{MC}(t) = R_S \tag{19}$$

When $d_{MC}(t) \le R_S$, the shielding condition is satisfied, i.e., $\chi_T(t) = 1$.

Within the effective time window $I = [t_{exp}, t_{exp} + 20]$, the window is scanned with a time step to capture the moments when $f(t) = d_{MC}(t) - R_S$ changes sign. Based on the value of the shielding indicator function, the shielding interval $I_0 = \{t \in I \mid \chi_T(t) = 1\}$ of the point target is constructed.

(4) Accurate Criterion for Complete Cylinder Shielding

Lemma: If the cylinder is completely shielded at a certain moment, the line of sight from the missile to any point on the cylinder must pass through the cloud cluster or the missile is inside the cloud; therefore, this moment must belong to the shielding interval I_0 of the point target [5].

To accurately describe the set of points on the cylinder boundary, the upper top surface, lateral generatrices, and lower base of the cylinder are parameterized as follows:

Upper top surface: $T(\rho, \phi) = T_0 + (0, 0, h_T) + \rho \cdot (\cos\phi, \sin\phi, 0)$, where $\rho \in [0, r_T]$, $\phi \in [0, 2\pi)$;

Lateral generatrices: $T(\rho, z) = T_0 + (\rho \cdot \cos\phi_0, \rho \cdot \sin\phi_0, z)$, where $\rho = r_T$, $z \in [0, h_T]$, $\phi_0 \in [0, 2\pi)$;

Lower base: $T(\rho, \phi) = T_0 + \rho \cdot (\cos\phi, \sin\phi, 0)$, where $\rho \in [0, r_T]$, $\phi \in [0, 2\pi)$.

By randomly selecting a face of the cylinder and generating definite values within the given parameter intervals, a point generation function for the cylinder boundary is obtained.

For a given time t, the necessary and sufficient condition for complete cylinder shielding is:

$$\Xi(t) = \mathbb{I}(\forall T \in \partial\text{Cylinder}, \|M(t) - C(t)\| \le R_S \text{ or } d_{MCT}(t) \le R_S) \tag{20}$$

Where ∂Cylinder denotes the boundary of the cylinder; $d_{MCT}(t)$ is the minimum distance from the center of the smoke cloud cluster to the line-of-sight segment formed by the i-th missile and a point on the cylinder boundary, satisfying:

$$d_{MCT}(t) = \min_{T \in \partial\text{Cylinder}} \|C(t) - (M(t) + s_{clip} \cdot (T - M(t)))\| \tag{21}$$

To obtain the closed-form solution of this minimum value, let $A = M(t)$, $B = T$, $P = C(t)$, and the optimal parameters are calculated as:

$$s_{opt} = \frac{(P-A)\cdot(B-A)}{\|B-A\|^2} \tag{22}$$

$$s_{clip} = \max(0, \min(1, s_{opt})) \tag{23}$$

Further, the expression for $d_{MCT}(t)$ is derived as:

$$d_{MCT}(t) = \|P - (A + s_{clip} \cdot (B - A))\| \tag{24}$$

Where the clip function restricts the value of s_{opt} to the interval [0, 1], ensuring compliance with the parameter range in geometric terms and thus accurately calculating the minimum distance.

The total shielding duration T_{total} is the measure of the shielding period, i.e.:

$$T_{total} = \int_{t_{exp}}^{t_{exp}+20} \Xi(t)dt = \sum_k (b_k - a_k) \tag{25}$$

Where $\mu(\cdot)$ is the measure function, and $\bigcup_k [a_k, b_k]$ is the union of shielding intervals, from which the total shielding duration is obtained by summing the lengths of each shielding interval.

2.2. Solution of Problem 1 Model

Interval refinement criterion: For any shielding interval obtained in the point target scenario, first divide it into sub-intervals, then find the sub-intervals with jumps in the cylinder shielding indicator function value and perform bisection until the jump points are found. The difference between the two jump points is the accurate interval of complete cylinder shielding.

To solve the model of Problem 1, the following steps are carried out:

STEP 1: Point target shielding interval. Select the center of the lower base of the cylinder as the point target, construct the shielding event function $f(t) = d_{MC}(t) - R_S$ for this point. Then scan within the effective time window $I = [t_{exp}, t_{exp} + 20]$ with a time step to capture the moments when f(t) changes sign. Based on the value of the shielding indicator function, the set of shielding intervals $I_0 = \bigcup_k [a_k, b_k]$ of the point target is obtained.

STEP 2: Interval refinement. For the shielding intervals obtained above, divide them with a time step of 0.01 s according to the interval refinement criterion; traverse inward point by point from both ends of each interval, randomly generate 100 sample points using the point generation function, and consider it complete shielding if all points satisfy the point shielding condition. When traversing to the moment of complete cylinder shielding, bisect the period formed by this moment and the previous moment, with the result accurate to 0.001 s.

STEP 3: Result output. After refining the shielding intervals of the point target, the corresponding accurate intervals of complete cylinder shielding are obtained as $\bigcup_k [a_k^*, b_k^*]$. Finally, output the difference between b_k^* and a_k^* as the total shielding duration.

2.3. Analysis of Problem 1 Results

The effective shielding period and total duration obtained by solving the above process are t_{start} = 8.038 s, t_{end} = 9.448 s, and T_{total} = 1.410 s.

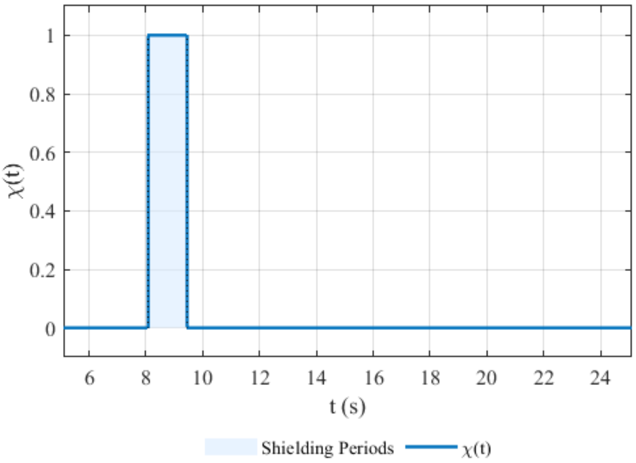

Figure 1. Variation of smoke shielding duration with time

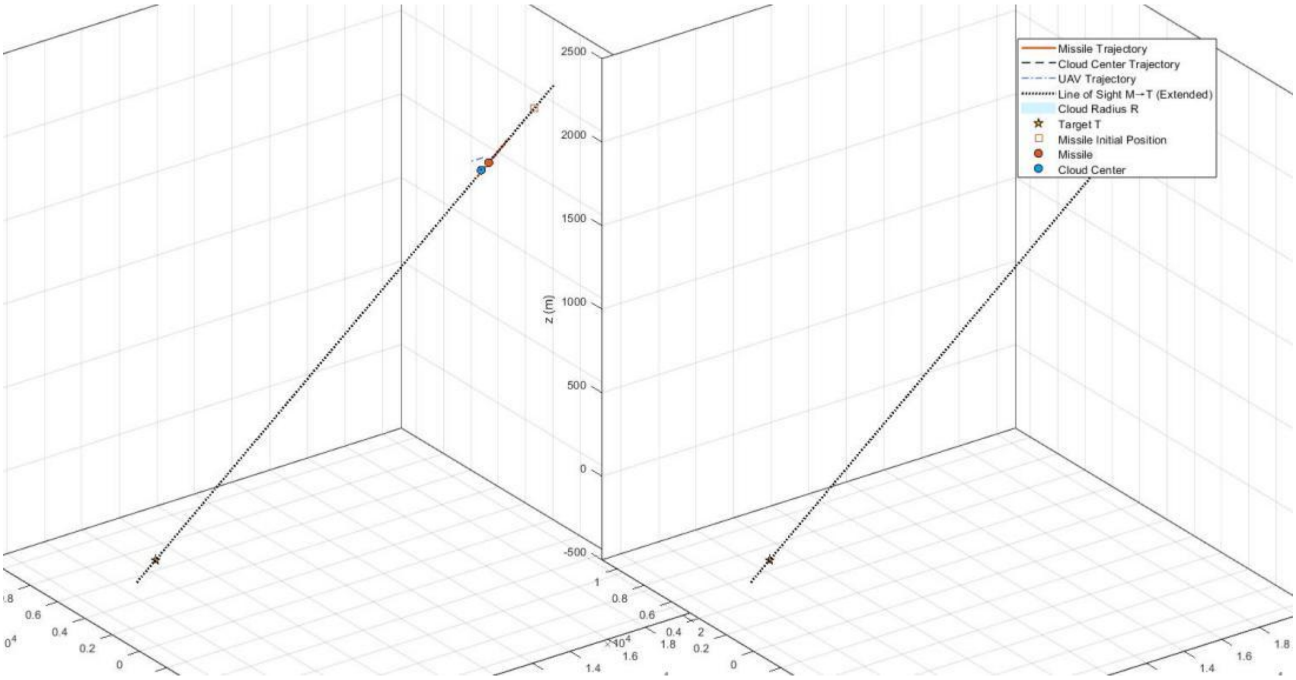

Figure 2. Trajectories of missile and cloud cluster and shielding status at multiple moments

From Figures 1 and 2, it can be seen that at the initial shielding moment ($t = 8.038$ s), the relative positions of the missile trajectory, UAV trajectory, and cloud sphere satisfy the sphere tangency condition, and the cloud cluster begins to produce shielding; at the end of shielding ($t = 9.448$ s), the relative positions of the three no longer satisfy the sphere tangency condition, and the shielding disappears.

3. Nonlinear Optimization Model for Single-UAV Single-Smoke-Grenade Deployment Strategy

3.1. Model Establishment

(1) Decision Variables

① Course angle θ

The course angle represents the flight direction of UAV FY1 in the horizontal plane, and its corresponding unit direction vector is $u_U = (\cos\theta, \sin\theta, 0)$. Adjusting θ can change the flight trajectory of the UAV, thereby affecting the position of the smoke interference bomb after release.

② Speed v_U

Speed represents the flight speed of UAV FY1. Different flight speeds directly affect the time it takes for the UAV to reach a specific position and the initial speed of the smoke interference bomb when released, thus having an important impact on the motion trajectory and spatiotemporal distribution of the effective shielding range of the smoke cloud cluster.

③ Release time t_{rel}

The release time refers to the time point when the UAV releases the smoke interference bomb. Choosing different release times will cause the smoke interference bomb to enter the motion process at different times, while also changing the start time of effective shielding formed by the smoke cloud cluster.

④ Fuze delay τ

The fuze delay is the time interval from the release of the smoke interference bomb to its detonation, and the detonation time is $t_{exp} = t_{rel} + \tau$. The fuze delay determines the time point at which the smoke cloud cluster forms effective shielding; a reasonable setting can make the smoke form effective shielding exactly when the missile reaches a critical position.

(2) Constraint Conditions

① UAV altitude constraint

As specified in the problem, the initial altitude of UAV FY1 is fixed, and it flies in a straight line at a constant altitude. Therefore, its vertical coordinate must satisfy:

$$U_z(t) = U_{0z} \ \forall t \geq 0 \tag{26}$$

Where U_{0z} is the initial vertical coordinate of the UAV.

② Effective evaluation window constraint

The smoke cloud cluster only has effective shielding capability for a period of time after detonation. Meanwhile, the time limit for the missile to hit the target must be considered. Therefore, the time to evaluate the smoke shielding effect must satisfy:

$$t \in [t_{exp}, \min(t_{exp} + 20, t_{hit})] \tag{27}$$

Where t_{hit} is the time when the missile hits the decoy target.

(3) Objective Function

To maximize the shielding time, the objective function is to maximize the effective smoke shielding duration:

$$\max_{v_U,\theta,t_{rel},\tau} T_{total} = \int_{\min(t_{exp},0)}^{\min(t_{exp}+20,t_{hit})} \Xi(t)dt \tag{28}$$

Where $\Xi(t)$ is the cylinder shielding indicator function, defined the same as in Problem 1.

(4) Establishment of Single-Objective Optimization Model

Based on the objective function and constraint conditions discussed above, we now present a single-objective optimization model for the maximum effective smoke shielding duration with the UAV course angle, flight speed, smoke interference bomb release time, and fuze delay as decision variables:

$$\begin{cases} \max\limits_{v_U,\theta,t_{rel},\tau} T_{total} = \int_{\min(t_{exp},0)}^{\min(t_{exp}+20,t_{hit})} \Xi(t)dt \\ \text{s.t.} \\ 70 \le v_U \le 140 \\ 0 \le \theta < 2\pi \\ t_{rel} \ge 0 \\ \tau \ge 0 \\ U_z(t) = U_{0z}\ \forall t \ge 0 \\ t_{exp} = t_{rel} + \tau \\ t_{hit} = \frac{\|M_0\|}{v_M} \end{cases} \quad (29)$$

3.2. Solution of Problem 2 Model

The genetic algorithm is a random search algorithm that simulates biological evolution, simulating natural selection and genetic laws. In this problem, decision variables such as the UAV course angle, speed, smoke release time, and fuze delay can be encoded as "chromosomes", with the smoke shielding duration as the fitness function. Through operations such as selection (selecting "chromosomes" with high fitness), crossover (exchanging "chromosome" genes), and mutation (randomly changing genes), iterative evolution is performed to finally find the parameter combination that maximizes the shielding duration. The specific implementation steps are as follows:

STEP 1: Individual and fitness. Determine the chromosome of an individual as $x = (v_U, \theta, t_{rel}, \tau)$. Each gene $v_U \in [70, 140]$ m/s, $\theta \in [0, 2\pi)$, $t_{rel} \in [0, 10]$ s, $\tau \in [0, 5]$ s. Mirror rebound is used when exceeding the bounds. The fitness function is $f(x) = T_{total}$, i.e., the shielding duration of the smoke cloud cluster on the cylinder within the 20 s time window after detonation. Calculations follow the process of Problem 1: first find the shielding interval using the center of the lower base of the cylinder as the point target, then refine each interval to 0.001 s using the refinement criterion, and finally obtain the length of the accurate shielding interval as T_{total}.

STEP 2: Initialization. Initialize a population of size 100, with each gene sampled uniformly. Meanwhile, add 20% heuristic individuals (approximately $v_U \approx 120$ m/s, $\theta \approx \pi$, $t_{rel} \in [0, 5]$ s, $\tau \in [0, 3]$ s). After evaluating all individuals, retain 10% elite individuals.

STEP 3: Evolution. In each generation of evolution, selection is performed through tournament selection (size 3) or ranking selection; crossover operation adopts the SBX method with a crossover probability $p_c = 0.9$ and a distribution index $\eta_c = 10$; mutation operation adds Gaussian noise to each gene, with the standard deviation corresponding to 5% of the interval length, followed by mirror rebound. After completing the operations, evaluate all individuals and retain 10% elite individuals to form the next generation.

STEP 4: Termination and output. Terminate evolution when the number of evolution generations reaches 200 or the improvement amount in 20 consecutive generations is less than 0.001 s. Output the optimal $x^* = (v_U^*, \theta^*, t_{rel}^*, \tau^*)$ and the corresponding union of shielding intervals. Optionally, perform one-dimensional refinement of each gene of x^* within a small range of ±0.5 s or the corresponding magnitude.

Its general process can be represented by the following pseudocode:

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Pseudocode 3: Genetic Algorithm (GA) Outer Optimization
Using the evaluation kernel as the "black-box fitness", search for $\theta, v_U, t_{rel}, \tau$ to maximize $T_{total}$

Given bounds:
$\theta \in [0,2\pi)$, $v_U \in [70,140]$,
$t_{rel} \in [0,10]$, $\tau \in [0,5]$
Initialize:
Population size $N = 100$, maximum generations $G_{max} = 200$, elite count $E = 10$, crossover probability $p_c = 0.9$, mutation probability $p_m = 0.1$, random seed
Generate N individuals $x = (\theta, v_U, t_{rel}, \tau)$ by uniform sampling (+ heuristic samples)
Loop for $gen = 1..G_{max}$:
Evaluate all individuals: $fitness(x) = T_{total} = Evaluate(x)$
Record the best individual $x_{best}$ of the current generation
Selection: Tournament selection or ranking selection
Crossover: Real-valued encoding (e.g., SBX), generate offspring, boundary mirroring/truncation
Mutation: Add Gaussian noise according to interval scale, mirror/truncate after mutation
Elite preservation: Copy the top E elites to the next generation
Convergence criterion: Stop if the improvement in $K = 20$ consecutive generations $<$ $tol = 0.001$ or $G_{max}$ is reached
Output:
$x^*$ = Global optimal solution, $Evaluate(x^*)$ to obtain $Segments^*$ and $T_{total}^*$
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3.3. Analysis of Problem 2 Results

Through calculations, the optimal total shielding duration is $T_{total}^* = 4.168$ s, the course angle $\theta^* = 3.142$ rad (180°), the corresponding unit direction vector $u_U^* = (-1,0,0)$, the flight speed $v_U^* = 118.5$ m/s, the release point $P_{rel}^* = (17622.25,0,1800)$ m, and the detonation point $C_0^* = (17185.95,0,1736.52)$ m. The shielding period is a continuous interval of 4.168 s.

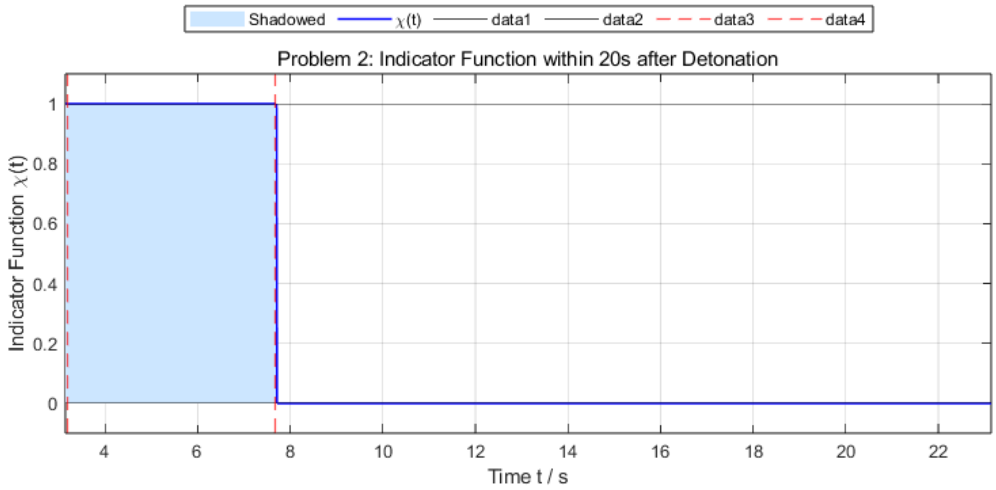

Figure 3. Variation of missile M1 shielding indicator function with time

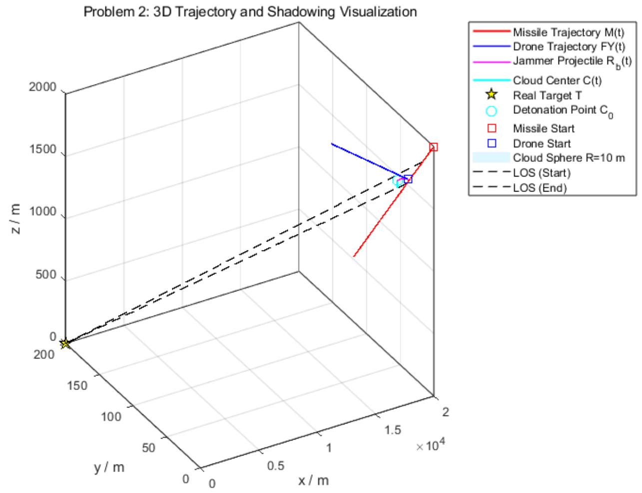

Figure 4. 3D schematic diagram of trajectories of missile, UAV, and cloud cluster

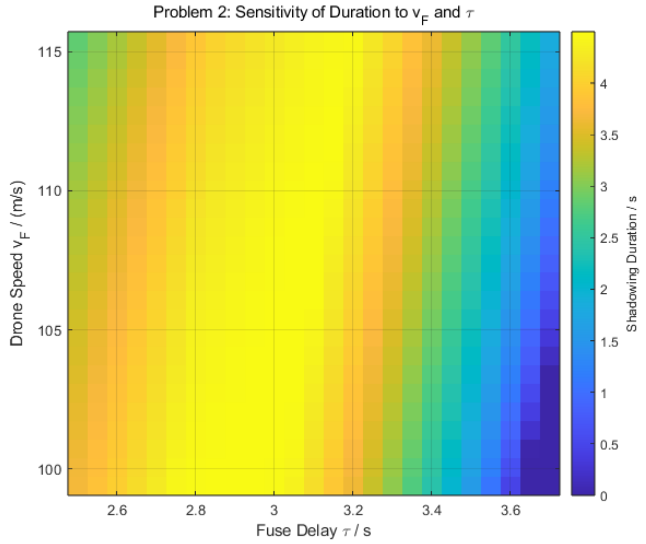

Figure 5. Heatmap of the impact of UAV speed and fuze delay on shielding duration

From Figure 3, it can be seen that in the initial stage (approximately 0 - 8 s), the value of the shielding indicator function is 1, indicating that the smoke bomb is in an effective shielding state, and then the value of the shielding indicator function drops to 0, and the shielding ends. This indicates that under the current parameter settings, the smoke has a good shielding effect on target M1.

Combined with Figure 4, the trajectories of UAV FY1, the smoke interference bomb, and target M1 are interrelated. The UAV flies in a specific direction and releases the interference bomb at an appropriate release point. The interference bomb moves along the trajectory to the detonation point, and the positional relationship between the formed smoke area and target M1 determines the shielding effect. The spatial distribution of the trajectory directly affects whether the smoke can effectively cover the target, thereby affecting the length of the shielding time.

From Figure 5, it can be seen that there is a significant parameter optimization interval between the fuze delay and the shielding duration. When the UAV speed is in the range of 104 - 118 m/s and the fuze delay is in the interval of 2.6 - 3.6 s, the shielding time shows an obvious increasing trend. In the cross area of speed and fuze delay, there are large yellow areas representing long shielding times, indicating that by reasonably matching these two parameters, the smoke shielding duration for the target can be effectively and significantly improved.

4. Conclusion

This study successfully achieves precise calculation of effective engagement duration and optimization of deployment strategies for dynamic targets using a single resource deployment.

For precision measurement, by constructing kinematic equations for the target, carrier, and post-deployment resource, and introducing the cylindrical coverage indicator function, we apply a high-precision binary search to determine the precise effective coverage period of the resource over the target, laying a solid foundation for subsequent optimization. For strategy optimization, we established a nonlinear single-objective optimization model with UAV attitude and deployment timing parameters as decision variables. Utilizing a simulated evolutionary genetic algorithm for search, we obtained the optimal parameter combination that maximizes the effective coverage duration. Future research should focus on enhancing the model's engineering applicability and optimization efficiency. Consider incorporating environmental factors like wind fields as stochastic processes into model assumptions and conducting perturbation robustness tests to enhance reliability under uncertainty. Simultaneously, to overcome the local convergence issue of genetic algorithms, explore integrating other local search techniques (e.g., one-dimensional refinement of the final population) or hybrid optimization algorithms to improve global optimization capabilities in complex objective function spaces.

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