Mathematical Modeling and Algorithm Application
ISSN: 3006-0842 | Vol. 6, No. 3, 2025

A Study on Spatio-Temporal Cooperative Optimization Model and Strategy for Single UAV Smokescreen Jamming

Xin Feng*

School of Software, Liaoning Technical University, Huludao, 125105, China
* **Corresponding author**: Xin Feng (Email: fx2144746479@163.com)

Abstract: This study addresses the strategy optimization problem of single UAV platforms deploying smokescreen jamming bombs in complex confrontation scenarios. Firstly, by establishing a mathematical model of missile kinematics and the spatial geometric relationship of smokescreen cloud formations, the effective coverage time for a single bomb against a single target was precisely calculated, providing a benchmark for subsequent optimization. Secondly, a multi-variable constrained optimization model was constructed, with UAV flight direction, speed, and smokescreen bomb deployment and detonation parameters as decision variables, and a grid search algorithm was employed to maximize the coverage effectiveness of a single jamming bomb. Finally, for the case of a single UAV deploying multiple jamming bombs, a multi-bomb cooperative deployment strategy based on temporal planning and spatial coverage was designed. By optimizing the deployment sequence using a grid search algorithm, the overall coverage time was significantly extended. Research results indicate that through precise spatio-temporal cooperative optimization, the single-bomb coverage time can be increased from a baseline of 1.405 seconds to 4.2 seconds, and the total coverage time can be further extended to 4.62 seconds under multi-bomb cooperation. This study provides a quantitative and operable method for single UAV smokescreen jamming strategies, offering reference value for tactical decisions in the field of electronic countermeasures.

Keywords: Smokescreen Jamming, Single UAV, Spatio-temporal Cooperative Optimization, Deployment Strategy, Coverage Effectiveness.

1. Introduction

In the face of the growing threat posed by precision-guided weapons in modern warfare, traditional passive defense measures have proven increasingly ineffective[1-2]. Against this backdrop, smoke-generating countermeasure flares, as an active defense measure, demonstrate flexible and mobile protective capabilities when integrated with unmanned aerial vehicle (UAV) platforms, leveraging their precise deployment and timed detonation capabilities[3-4]. However, despite continuous advancements in smoke countermeasure technology, relying solely on conventional methods remains insufficient to effectively resist multi-directional saturation attacks. How to achieve precise control over the spatiotemporal coverage of smoke screens by optimizing the deployment and detonation strategies of countermeasure grenades has become a critical issue for enhancing the survivability and system-level combat effectiveness of UAV platforms. This study aims to provide theoretical support for cutting-edge fields such as intelligent UAVs and adaptive defense by addressing the collaborative decision-making and optimization problems of smoke countermeasure grenades under a single UAV platform, thereby advancing the evolution of national defense technology toward intelligence and networking[5].

To enhance the smoke-based jamming effectiveness of a single UAV platform, this study first focuses on evaluating the effective shielding duration of a single smoke-based decoy deployed by a single UAV against an incoming missile. Building upon this foundation, the research delves deeper into how optimizing both the UAV's flight parameters and the deployment/detonation parameters of the smoke decoy can maximize the effective shielding duration of a single decoy. Ultimately, when a single drone must deploy multiple smoke decoys, this paper aims to design a coordinated deployment strategy for multiple decoys to achieve optimal and sustained effective masking time against missiles[6-7].

To address these challenges, this study proposes a modeling and solution method based on spatiotemporal cooperative optimization. At the foundational evaluation level, a mathematical model of the spatial geometric relationship between missile kinematics and smoke cloud distribution is established. Combining constraints such as effective radius and effective duration post-detonation, a time-integral model is employed to precisely calculate the baseline masking duration for a single target using a single flare. Building upon this foundation, a multi-variable constrained optimization model is constructed to maximize single-smoke-grenade effectiveness. Key decision variables include UAV flight direction, velocity, and smoke-grenade deployment/detonation delays. A two-stage grid search algorithm is employed for global optimization. Finally, for multi-smoke-grenade coordination strategies, this paper designed a collaborative deployment model based on temporal planning and spatial coverage. By introducing deployment interval constraints and again utilizing the grid search algorithm to optimize the deployment sequence and detonation timing of multiple smoke grenades, the model aims to achieve effective temporal and spatial coordination of the smoke barrage. This coordination ensures seamless and extended effective concealment duration, thereby significantly enhancing the overall jamming effectiveness[8].

The symbolic variables used in this study and their descriptions are listed in the table 1.

Table 1 Symbols and Explanations

Symbol	Description	Unit
M_0	Initial Position of M1	/
$M(t)$	Spatial Position of M1 Missile at Any Time t	/
F	False Target Position	/
T	True Target Position	/
$\hat{m}$	Missile Unit Flight Direction Vector	/
P_{drop}	Smoke Decoy Deployment Position	/
P_{det}	Smoke Decoy Explosion Position	/
P_{close}	Distance from Smoke Cloud Center to Nearest Point on Projection Line Segment	/
z	Vertical coordinate of smoke decoy's free-fall motion	m
z_d	Height coordinate of smoke decoy release point	m
z_e	Height coordinate of smoke decoy detonation point	m
$C(t)$	Center position of smoke cloud	/
λ	Projection parameters	/
$d_{\min}$	Shortest distance from smoke cloud center to projection line segment	m
v_{sink}	Constant sinking velocity of smoke cloud after detonation, valued at 3 m/s	m/s
$z_c(t)$	Sinking trajectory of cloud center over time	

2. Benchmark Evaluation of Smoke Jammer Effectiveness for Single-UAV Single-Projectile Smoke Disruption

2.1. Data Preprocessing

The first section primarily focuses on the FY1 drone's single decoy shielding against the M1 missile. First, basic kinematic parameters such as the missile's and drone's movement directions are processed. Given that the M1 missile is flying toward the decoy target, its flight direction vector can be easily calculated as [-20000, 0, -2000] based on their known coordinates.

Given the UAV's horizontal flight path toward the decoy target, its direction vector is determined as [-1, 0, 0].

The 1.5-second delay for bomb release and 3.6-second delay for detonation constitute the fundamental time framework for this problem, with 5.1 seconds serving as the critical time threshold for determining effective jamming.

Additionally, a three-dimensional model of the real target was established as a cylinder with a base centered at (0, 200, 0), a radius of 7 meters, and a height of 10 meters. This serves as the geometric foundation for subsequent calculations determining whether the cloud effectively obscures the real target. Enlarged 3D View of Target Area is shown in figure 1.

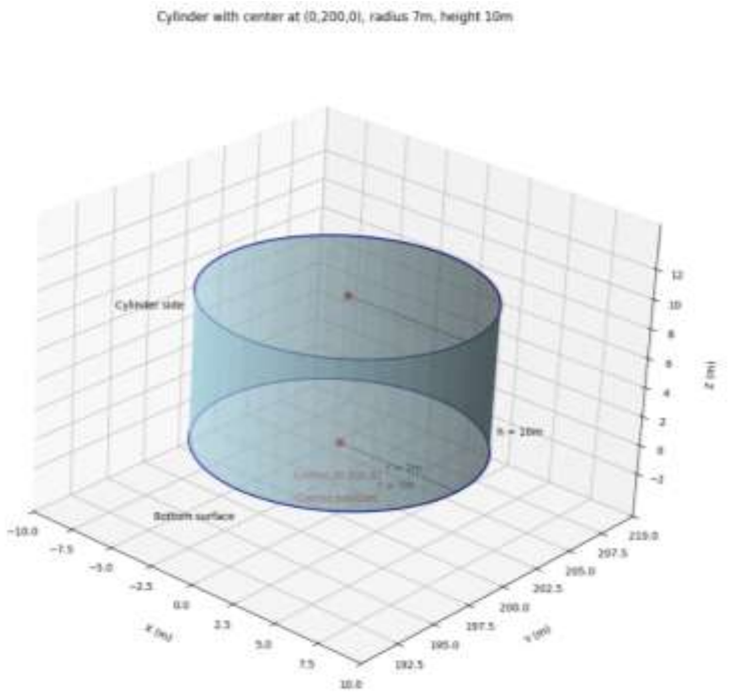

Figure 1: Enlarged 3D View of Target Area

2.2. Model Development

Based on the analysis in the first subsection, this study constructs an accurate occlusion effectiveness evaluation model for single-missile smoke screen interference targeting the M1 missile. This model leverages principles of kinematics and spatial geometry to quantitatively calculate the duration of effective occlusion by analyzing the spatio-temporal relationship between the missile's line of sight and the smoke cloud.

By calculating the vertical distance from the smoke center to the missile-target line-of-sight segment, the model accurately determines the occlusion state. Employing a fine-grained time-discretization strategy, the system systematically scans the entire operational cycle to precisely capture critical occlusion thresholds, ultimately outputting a segmented occlusion time series.

2.3. Solving the model

This study establishes an accurate model based on geometric projection and kinematic principles. By analyzing spatial geometric relationships, it determines whether smoke clouds effectively block the line of sight between the missile and the real target, thereby calculating the effective duration of smoke decoy interference for the M1.

First, starting from the initial position $M_0 =$ （20000,0,2000） of the M1 and ending at the position $F = (0,0,0)$ of the decoy target, vector operations are performed to derive the unit flight vector of the missile.

$$\hat{m} = \frac{\text{F-M}_0}{\|\text{F-M}_0\|}$$

As indicated in the question stem, the flight speeds of the missile and drone were processed during data preprocessing, yielding the drone's direction vector as [-1, 0, 0]. This allows calculation of the spatial coordinates of both the missile and drone at any given time t:

$$M(t) = M_0 + 300 \times t \times \hat{m}$$
$$P_{\text{drop}} = (17800,0,1800) + 120 \times 1.5 \times [-1,0,0]$$

From this, we can calculate that the munition deployment point will be at coordinate $[16000,0,1800]$ after 1.5 seconds. Based on this coordinate, the smoke grenade deployment can be calculated by considering the effects of inertia and gravity. The smoke grenade's coordinates along the x, y, and z axes can be determined as follows: - Vertically, the smoke grenade undergoes free-fall motion. Its displacement along the z-axis is $\Delta z = -\frac{1}{2} \times 9.8 \times (3.6)^2$, while its y-axis position remains unchanged. - Horizontally, its displacement along the x-axis is $120 \times 3.6 \times [-1,0,0]$. Therefore, the detonation point coordinates can be calculated as:

$$p_{\text{det}} = P_{\text{drop}} + 120 \times 3.6 \times [-1,0,0] + [0,0，\Delta z]$$

After detonation, the cloud mass descends at a constant velocity of 3 m/s while maintaining a spherical shape with a 10-meter effective radius. At any given time t($t \geq 3.6s$), the center of the cloud mass is located at: $C(t) = P_{\text{det}} + [0,0，-3 \times (t - 5.1)]$.

The occlusion determination mechanism employs geometric projection principles. At each calculation point, the line segment between the missile's current position $M(t)$ and the true target $T = (0,200,0)$ is first identified, followed by calculating the shortest distance from the cloud cluster center $C(t)$ to this segment. The projection parameter $\lambda = \frac{(C(t)-M(t)\cdot(T-M(t)))}{\|T-M(t)\|^2}$ is obtained via vector projection methods. Constraining λ within the interval [0,1] ensures the projection point lies on the line segment. The closest point is denoted as $P_{\text{close}} = M(t) + \lambda \cdot (T - M(t))$, and the shortest distance as $d_{\min} = \|C(t) - P_{\text{close}}\|$. When $d_{\min} \leq 10m$, it is judged as a valid occlusion.

During the computational process, this paper employs a time step of 0.005 seconds for numerical calculations, advancing the solution throughout the entire masking cycle (5.1 seconds to 25.1 seconds). By systematically traversing the entire time domain, all time points satisfying the masking conditions are recorded. Ultimately, a state change detection algorithm extracts the continuous masking periods and their respective durations.

The computational results indicate that under this deployment strategy, the smoke-generating decoy successfully created an effective masking period for the M1 missile, with a total masking duration of 1.405 seconds.

2.4. Analysis of Results

Based on numerical simulation results, the effective masking duration of 1.405 seconds reveals the spatiotemporal coupling characteristics between high-speed moving targets and slowly settling smoke screens. This quantitative finding demonstrates the efficacy and underlying principle of the single-missile interference strategy.

The two-order-of-magnitude difference between the missile's flight velocity of 300 m/s and the cloud mass settling velocity of 3 m/s results in a pronounced temporal scale separation within the system. Calculations indicate the missile traverses the 10-meter effective radius spatiotemporal window in just 0.033 seconds, a timescale defining the transient nature of the masking event. The measured total duration of 1.405 seconds comprises multiple discrete time segments, confirming the intermittent nature of high masking effects.

System performance is constrained by three coupled factors: spatio-temporal synchronization determines the activation timing of the masking window, the time-varying height difference influences masking duration, and geometric configuration governs triggering conditions. Together, these form a complex nonlinear system where minor parameter shifts can cause significant fluctuations in masking duration.

Concurrently, the geometric projection model established in this study successfully quantifies the dynamic characteristics of smoke interference. Although the 1.405-second masking duration is insufficient for sustained protection, it reaches the critical threshold for disrupting terminal guidance systems. Modern precision-guided munitions require continuous target lock-on during terminal guidance; even microsecond-level interruptions in obscuration can cause guidance sequences to fail. This finding confirms the potential value of single-munition solutions while revealing their inherent limitations: within a given parameter space, single-munition obscuration duration faces an insurmountable theoretical upper bound. Variation in Missile and Smoke Screen Height are shown in figure 2.

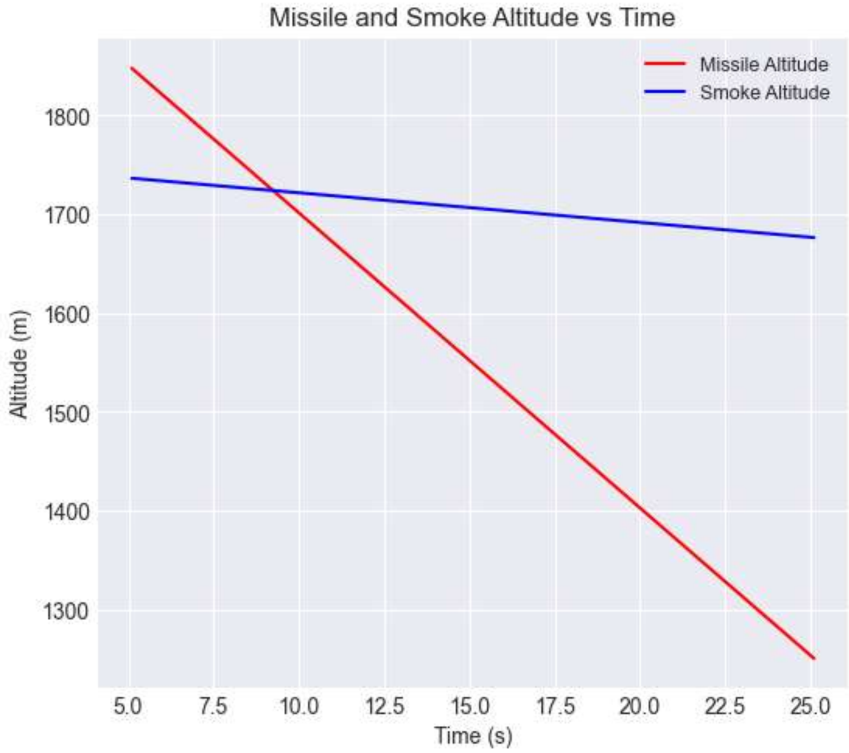

Figure 2: Variation in Missile and Smoke Screen Height

3. Research on Enhancing the Shielding Effectiveness of Single Smoke Decoy Flares Based on Multi-Parameter Optimization

3.1. Data Preprocessing

In the second subsection, establish a unified spatial coordinate system based on the fundamental parameters provided in the problem statement. The initial coordinates of the missile and drone, along with the missile's flight direction vector, remain identical to those in the first subsection.

When calculating the drone's flight direction, angular measurements are converted to radians, with true east defined as 0° and angles increasing counterclockwise. Time parameters are discretized using a fixed time step of 0.02 seconds to balance computational efficiency and accuracy.

Smoke characteristics are modeled using a spherical model. A 10-meter effective radius serves as the spatial distance criterion, with a 3 m/s sinking velocity calculated linearly over discrete time steps. The influence of gravitational acceleration (9.8 m/s^2) is accounted for through direct vector operations to compute position coordinates at each time step, thereby avoiding errors associated with numerical integration methods.

3.2. Model Development

In the solution of the second subsection, a multi-parameter optimization model based on kinematic and geometric constraints is constructed to achieve the objective of maximizing effective shielding for missile M1 through the deployment of a single FY1 smoke decoy by the UAV.

The objective function is defined as the effective concealment duration of the smoke cloud over the line connecting the missile and the true target (0, 200, 0). This is achieved through temporal discretization and geometric evaluation: at each time step, the perpendicular distance from the cloud's center to the missile-true target line is calculated. If this distance is less than 10 meters and the foot of the perpendicular lies within the line segment, that time point is counted as effective concealment.

The solution process employs a two-stage grid search method. The first stage conducts coarse-grained search across the global parameter space to identify regions of potential optimal solutions. Subsequently, fine-grained search is performed within these regions to enhance solution quality and accuracy.

3.3. Model Solving

This study employs a multi-parameter optimization model based on kinematic and geometric constraints, utilizing systematic numerical methods to extend the effective screening duration of smoke-interference grenades.

The missile trajectory calculation method aligns with Section 1. Given the initial position of the UAV as $U_0 = (17800,0,1800)$, the calculation process defines the heading angle as θ (in radians) and velocity as v, where $v \in [70,140]$. Consequently, the velocity equation for UAV FY1 is derived as:

$$v_{\text{uav}} = v \cdot (\cos\theta, \sin\theta, 0)$$

The smoke grenade deployment point t_d occurs at time $P(d) = U(t_d)$, with detonation time $t_e = t_d + \Delta t$. When calculating the detonation point, analysis is conducted separately in both horizontal and vertical directions. Horizontally, due to the inertia imparted to the smoke grenade by the drone, its position-time relationship is $P_{e,\ h} = P_d + v_{\text{uav}} \cdot \Delta t$. Vertically, considering gravitational acceleration $g = 9.8\text{m/s}^2$, its position equation is $z_e = z_d - \frac{1}{2} g (\Delta t)^2$.

After detonation, the cloud mass moves at a constant velocity, with its descent trajectory described by $z_c(t) = z_e - v_{\text{sink}} \cdot (t - t_e), t \geq t_e$ where $v_{\text{sink}} = 3\text{m/s}$.

For effective concealment geometry, the true target position is $T = (0,200,0)$, at any time t. If the distance from the cloud center $C(t)$ to the line connecting the missile position $M(t)$ and the true target T satisfies: $d(t) = \frac{\|C(t)-M(t)\times(T-M(t))\|}{\|T-M(t)\|} \leq R$. Where $R = 10m$, and the foot of the perpendicular lies on segment $M(t)T$, indicating the missile cannot detect the true target at this moment, which is considered effective concealment.

The process employs a two-stage grid search method to optimize the following decision variables: heading angle $\theta \in [150°, 210°]$, flight speed $v \in [90,140]$m/s, release time $t_d \in [0.5,4.0]s$, and detonation delay $\Delta t \in [2.0,7.0]s$.

During the coarse search phase, uniform sampling is performed within the parameter ranges: 13 points for heading angle, 6 points for speed, 7 points for release time, and 7 points for delay, yielding a total of 13 × 6 × 7 × 7 = 38,221 combinations. The effective shielding duration was calculated for each combination, yielding the initial optimal solution: $\theta = 178.8446°, v = 98.333\text{m/s}, t_d = 1.167s, \Delta t = 3.426s$. During the fine-search phase, a denser grid was constructed within the coarse solution neighborhood (9 points for heading angle, 7 points for speed, 7 points for release time, 7 points for delay) for refined exploration, ultimately determining the globally optimal parameter combination.

Finally, key position points are calculated based on the optimal parameters:

The deployment point is $P_d = (17800,0,1800) + 98.333 \cdot (\cos(178.846°), \sin(178.846°), 0) \cdot 1.167$, yielding deployment point result: $(17348.227, 9099, 1742.400)$.

The final effective shielding duration is 4.2 seconds. This result demonstrates that the aforementioned optimization method successfully determines the drone deployment strategy that maximizes shielding time.

3.4. Analysis of Results

A systematic analysis of the optimization results from the second subsection demonstrates that the acquired deployment strategy achieves a significant enhancement in temporal shielding effectiveness through multi-parameter collaborative optimization. The optimal solution indicates that the UAV should adopt a heading angle of 178.846° and a flight speed of 98.333 m/s, execute deployment 1.167 seconds after mission commencement, and detonate 3.429 seconds later, ultimately achieving an effective shielding duration of 4.2 seconds.

Spatially, this heading angle positions the UAV laterally relative to the missile's trajectory. The spatial configuration of the deployment point (17685.301, 2.310, 1800) and detonation point (17348.227, 9.099, 1742.400) ensures optimal spatiotemporal alignment between the cloud cluster's descent path and the missile's flight path. Additionally, the combination of a moderately low flight speed and an earlier deployment time effectively coordinates the timing relationship between cloud formation and missile arrival.

This strategy achieves multiple optimizations: spatial positioning avoids the missile's impact path, and within the 20-second cloud duration, it delivers 4.2 seconds of effective interference. This outcome provides theoretical support and tactical guidance for UAV electronic countermeasure operations, demonstrating the significant value of multi-parameter optimization in complex combat scenarios. Visualization of the Optimal Strategy for Three Smoke Distraction Grenades is shown in figure 3.

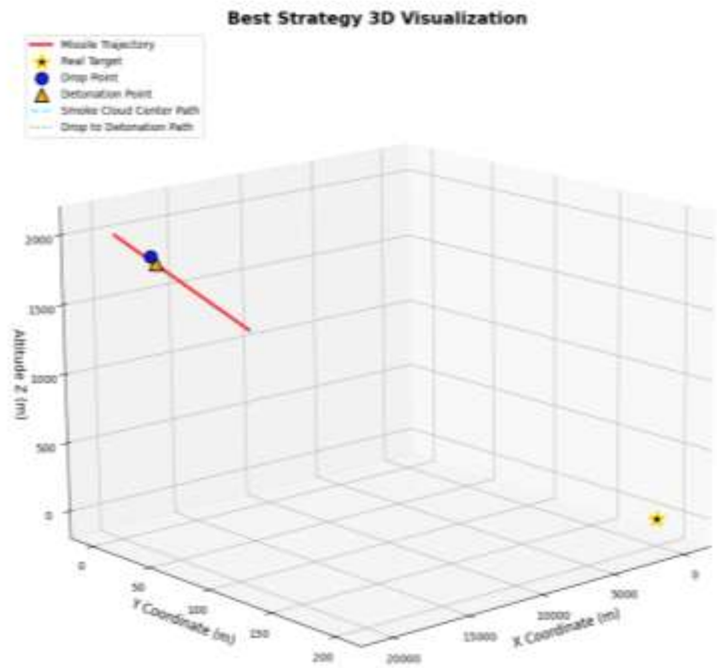

Figure 3: Visualization of the Optimal Strategy for Three Smoke Distraction Grenades

4. Research on Spatio-Temporal Coordinated Deployment Strategy and Effectiveness Extension for Multiple Smoke Decoy Bombs by a Single UAV

4.1. Data Preprocessing

For the data preprocessing in the third subsection, the focus lies on the temporal coordination and spatial configuration of multi-missile collaboration. The interval between adjacent launches must be ≥1 second, with the detonation time of each missile independently controlled.

The characteristics of smoke cloud formations require precise modeling using small-step, long-duration discretization to ensure computational accuracy. Missile trajectories are evaluated against spatial geometric relationships to determine if they enter the cloud's effective concealment range.

The core of the multi-missile strategy lies in coordinating the deployment timing, detonation timing, and spatial positioning of three missiles to maximize overlapping concealment periods. Total effective concealment duration is calculated using a time-merging algorithm.

4.2. Model Development

The third subsection establishes the model based on the conditions for multi-missile coordinated jamming. First, determine the trajectory of missile M1 as it flies in a straight line from its initial position toward the decoy target. UAV FY1 serves as the deployment platform, selecting flight direction and speed within specified limits while maintaining level, straight-line flight.

The deployment of three decoy flares requires strict timing: adjacent deployment intervals ≥ 1 second. By coordinating the spatio-temporal parameters of all three flares, the combined total masking duration is maximized, thereby optimizing the solution. A grid search is employed to identify the optimal drone flight parameters and deployment/detonation timing sequence within the decision space, ultimately outputting the strategy combination yielding the longest masking duration.

4.3. Solving the model

For the third subsection, deploy three smoke decoy flares using the FY1 drone to interfere with the M1. Establish a multi-flares coordinated optimization model based on kinematic and geometric constraints. The model inherits the core variable definitions from the previous two questions: missile position $M(t) = M_0 + v_m \cdot t$, direction vector $\hat{m} = \frac{\text{F-M}_0}{\|\text{F-M}_0\|}$, drone motion equation $U(t) = U_0 + v_{\text{uav}} \cdot t$, and heading angle θ as decision variables.

For the three smoke decoys, introduce decision variables: deployment time $t_{\text{d1}}, t_{\text{d2}}, t_{\text{d3}}$ and detonation delay $\Delta t_1, \Delta t_2, \Delta t_3$, subject to constraint $t_{\text{d2}} - t_{\text{d1}} \geq 1, t_{\text{d3}} - t_{\text{d2}} \geq 1$. The deployment point $P_{\text{di}} = U(t_{\text{di}})$ and detonation point horizontal position $P_{\text{ei},\ h} = P_{\text{di}} + v_u \cdot \Delta t_i \cdot (\cos\theta, \sin\theta, 0)$, vertical position $z_{\text{ei}} = 1800 - \frac{1}{2} g (\Delta t_i)^2$ of the ith decoy satisfy $g = 9.8\text{m/s}^2$. The descent trajectory of the cloud center post-detonation is: $C_i(t) = \left(P_{ei,h,x}, P_{ei,h,y}, z_{ei} - v_{sin\,k} \cdot (t - t_{ei})\right)$,where $t_{e_i} = t_{\text{di}} + \Delta t_i$ (24) , $v_{\text{sink}} = 3\text{m/s}$, .

Effective masking determination follows the same criteria as above. Grid search is employed to optimize decision variables:

$\theta \in [150°,\ 210°], v_u \in [70,140], t_{d1} \in [1,3], t_{d2} \in [2,5], t_{d3} \in [3,6], \Delta t_1, \Delta t_2, \Delta t_3 \in [2,6]$, satisfying the deployment interval constraint. A coarse search identifies potential optimal regions, followed by a fine search to obtain the global optimum: $\theta = 180°, v_u = 140m/s, t_{d1} = 1.0s, t_{d2} = 2.0s, t_{d3} = 3.0s, \Delta t_1, \Delta t_2, \Delta t_3 = 2.0s$.

Calculate key positions:

Deployment point $P_{d1} = (17800,0,1800) + 140 \times 1.0 \times (-1,0,0) = (17660,0,1800)$ for the first flare.

Detonation point $P_{e1} = (17660,0,1800) + 140 \times 2.0 \times (-1,0,0) + \left(0,0,-\frac{1}{2} \times 9.8 \times 4\right)$ yields result $(17100,0,1721.6)$. Deployment point $P_{d2} = (17800,0,1800) + 140 \times 2.0 \times (-1,0,0) = (17100,0,1800)$ for the second flare.

Detonation point $P_{e2} = (17100,0,1800) + 140 \times 2.0 \times (-1,0,0) + \left(0,0,-\frac{1}{2} \times 9.8 \times 4\right)$, yielding result $(16260,0,1623.6)$. Third deployment point $P_{d3} = (17800,0,1800) + 140 \times 3.0 \times (-1,0,0) = (16960,0,1800)$.

Detonation point $P_{e3} = (16960,0,1800) + 140 \times 2.0 \times (-1,0,0) + \left(0,0,-\frac{1}{2} \times 9.8 \times 4\right)$, yielding result $(16120,0,1623.6)$.

Calculations employed a time step of 0.02s. By traversing the time domain and merging coverage periods, the effective coverage durations were determined as: first deployment 2.6s, second deployment 1.56s, third deployment 0.46s, totaling 4.62s.

4.4. Analysis of Results

For the third subsection, this paper establishes a multi-decoys coordinated spatio-temporal optimization model to achieve maximum concealment of the M1 missile by coordinating the deployment timing and spatial distribution of three smoke decoy flares. The model precisely describes the trajectories of the missile, UAV, and decoys based on kinematic equations. It employs geometric projection principles to assess masking effectiveness and utilizes a grid search algorithm to optimize parameters within a six-dimensional decision space (UAV heading angle, flight velocity, deployment times of the three decoys, and detonation delays). Numerical calculations demonstrate that optimal concealment is achieved when the UAV flies at a heading angle of 180° (opposite the pseudo-target direction) at 140 m/s, with the three decoys deployed at 1.0 s, 2.0 s, and 3.0 s respectively, all using a 2.0 s detonation delay.

The three decoys form a progressive spatial concealment sequence: The first decoy detonation point (17100,0,1721.6) provided 2.6 seconds of shielding, the second (16260,0,1623.6) provided 1.56 seconds, and the third (16120,0,1623.6) provided 0.46 seconds. Results show that the descent trajectories of the three cloud clusters intersect multiple times with the missile flight path. Although partial temporal overlap exists, the total effective masking duration reaches 4.62 seconds through a time-merging algorithm.

Thus, while the equidistant deployment and unified detonation strategy simplifies coordination, the third decoy's shielding effectiveness significantly diminishes due to the missile's proximity to the actual target and the cloud cluster's lower descent altitude. This strategy fully leverages the spatial coverage advantages of multi-decoys, providing an optimal spatiotemporal configuration for deploying three decoys from the FY1 UAV. Visualization of the Optimal Strategy for Three Smoke Distraction Grenades is shown in figure 4.

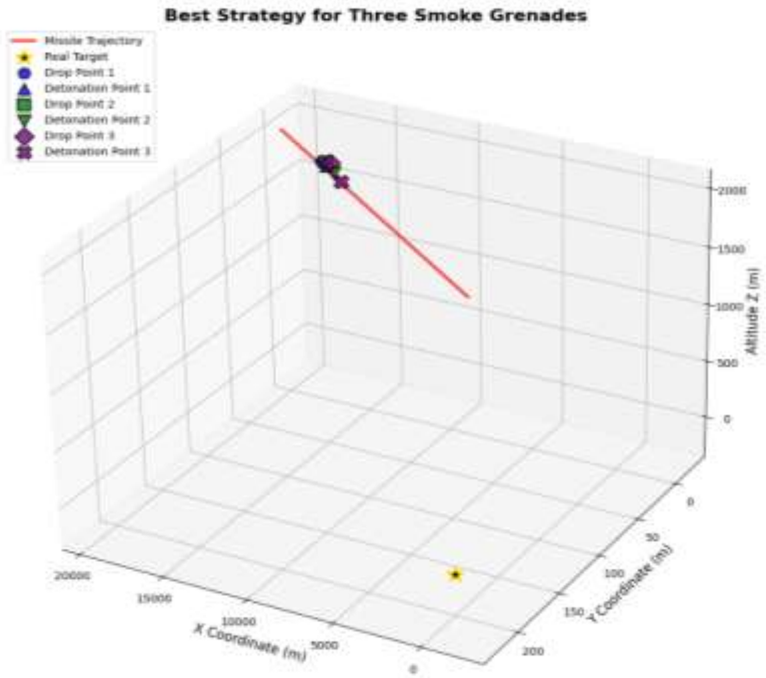

Figure 4: Visualization of the Optimal Strategy for Three Smoke Distraction Grenades

5. Conclusions

This study delves into the strategic optimization of maximizing target concealment effectiveness by deploying smoke-generating decoys from a single UAV platform against precision-guided weapon threats. Through establishing sophisticated mathematical models and applying advanced optimization algorithms, the research yields the following key conclusions:

First, in evaluating the baseline concealment effectiveness of a single UAV deploying a single smoke decoy, we successfully constructed a mathematical model capturing the spatial geometric relationship between missile kinematics and the smoke cloud. Based on rigorous concealment criteria and a duration-integration model, we precisely calculated that under specified parameters, a single decoy provides 1.405 seconds of effective concealment against an M1 missile. This quantitative result not only reveals the inherent spatiotemporal coupling characteristics between high-speed moving targets and slow-descending smoke clouds but also establishes a reliable baseline for subsequent optimization research.

Second, to significantly enhance the shielding efficacy of a single smoke decoy, this study constructed a multivariate constrained optimization model. Key decision variables included the UAV's flight direction, velocity, and the deployment/detonation parameters of the smoke decoy. By employing a two-stage grid search algorithm for systematic optimization, the optimal parameter combination was successfully identified. This resulted in a substantial increase in the effective shielding duration per decoy, rising from the baseline 1.405 seconds to 4.2 seconds. This achievement fully demonstrates that precise parameter tuning can substantially enhance the jamming effectiveness of a single platform, providing robust theoretical support and tactical guidance for UAV electronic countermeasure operations.

Finally, addressing the spatiotemporal coordination strategy for deploying multiple smoke grenades from a single UAV, this study designed a coordinated deployment strategy based on temporal planning and spatial coverage models, aiming to achieve continuous and effective target concealment. While satisfying the deployment interval constraint (≥1-second gap between adjacent deployments), the grid search algorithm optimized the sequence and detonation timing of multiple smoke grenades, ultimately extending the total effective masking duration to 4.62 seconds. Although partial temporal overlap exists during multi-grenade coordination, this strategy effectively achieves seamless transition and extension of masking duration through spatiotemporal synergistic effects of the grenade barrage, providing an actionable solution for coordinated multi-munition operations.

In summary, this study provides a quantitative and actionable methodology for single-UAV smoke interference strategies. From baseline evaluation and single-munition optimization to multi-munition coordination, the findings not only deepen understanding of smoke interference dynamics but also offer significant reference value for tactical decision-making in electronic countermeasures and the optimized design of future air defense and missile defense systems.

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