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Quantitative Study on the Effective Shielding Time Window of UAV Smoke Grenades Based on Geometric Determination and Kinematic Comparison

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Abstract: This study aims to quantify the effective duration of concealment provided by a single smoke grenade against an incoming missile, thereby optimizing the deployment strategy for drone smoke decoy grenades. Following a problem decomposition—model construction—precise solution framework, this work employs kinematic modeling and geometric detection. Within a unified coordinate system, it extracts the shielding time window and cumulative shielding duration through time-domain scanning with a fixed time step. To investigate aerodynamic effects, the model performs dynamic comparisons between drag-free flight at constant altitude and flight incorporating quadratic drag. The drag-inclusive model employs fourth-order Runge–Kutta numerical advancement. Results indicate: under no-drag conditions, the masking duration is 1.394 s with a minimum distance of 4.669 m; introducing quadratic drag increases masking duration to 1.809 s while reducing the minimum distance to 2.952 m, validating the positive gain from drag. The model converged through sensitivity analysis, demonstrating robust conclusions.

Keywords: Geometric determination, Numerical integration, Smoke shielding quantification.

1. Introduction

In modern air defense and missile defense systems, electro-optically guided missiles pose a significant threat to ground targets. As a low-cost soft defense measure, drone-launched smoke countermeasure grenades can form smoke clouds to obscure real targets, effectively blocking missile guidance lines of sight [1]. The effectiveness of such countermeasures hinges on the precise timing and placement of the smoke screen to ensure the target is concealed during the missile's terminal approach phase.

Currently, research on smoke screen effectiveness primarily focuses on two aspects: the physical properties of the smoke (e.g., dispersion characteristics, spectral attenuation) [1] and the tactical deployment strategies (e.g., launch angles, patterns for multiple grenades). However, a critical gap exists in quantitatively determining the precise effective shielding time window of a single smoke grenade against a specific, fast-moving threat. Existing studies often rely on simplified kinematic assumptions or lack a rigorous, time-resolved geometric analysis of the dynamic interaction between the evolving smoke cloud, the missile's trajectory, and the line-of-sight [2, 3]. Many models do not fully account for the aerodynamic effects on the grenade's trajectory post-release, which can significantly alter the detonation point and, consequently, the spatiotemporal evolution of the smoke screen.

Therefore, the key issue addressed in this paper is the development of a high-fidelity model to determine the effective obscuration duration of a single smoke grenade against an incoming missile with precisely defined parameters [2]. The unique contribution of this work lies in its integrated "trajectory propagation-smoke cloud evolution-geometric determination-time accumulation" solution chain, implemented within a unified coordinate system. Unlike previous approaches, this study introduces two core advancements:

A precise geometric determination method: It employs a time-domain scanning technique with a fixed step size to extract the exact shielding time window and cumulative duration, based on the shortest distance between the smoke cloud center and the missile-target line-of-sight segment.

A dynamic comparative analysis: To investigate the impact of aerodynamic drag, the model performs a systematic comparison between a simplified drag-free flight model and a more realistic model incorporating quadratic drag, solved using a fourth-order Runge-Kutta numerical integration scheme.

This framework allows for a clear quantification of the drag effect's contribution to shielding effectiveness. The model's robustness is further validated through sensitivity analysis. By addressing these aspects, this study provides a more accurate and reliable basis for optimizing the deployment strategy of drone smoke decoy grenades, offering a significant improvement over existing methodologies that often overlook these nuanced dynamic and geometric factors.

2. Coordinate System Establishment

To align with the spatial description in the problem statement and ensure seamless integration of subsequent dynamics and geometric criteria, a 3D Cartesian coordinate system (x, y, z) is adopted [4]. The decoy target serves as the origin $O=(0,0,0)$, with the initial position of the missile denoted as M_0, the initial position of the UAV as P_0, and the center of the bottom surface of the real target as $T=(0,200,0)$. On this basis, the unit vector of the missile's flight direction is defined as:

$$e_{M1}=\frac{O-M_0}{|O-M_0|} \quad (1)$$

For the UAV in the "constant altitude level flight" scenario, since it maintains a constant altitude, the unit vector of its horizontal flight direction is naturally expressed as:

$$e_{FY1}^{level}=\frac{(O_x-P_{0x},O_y-P_{0y},0)}{|(O_x-P_{0x},O_y-P_{0y},0)|} \quad (2)$$

Meanwhile, to form a comparison and verify the necessity of the constant altitude assumption, a 3D flight direction of the UAV "directly pointing to the origin" is introduced:

$$e_{FY1}^{3D}=\frac{O-P_0}{|O-P_0|} \quad (3)$$

The unit vector operator is defined as:

$$\text{unit}(a)=\frac{a}{|a|} \quad (4)$$

This 3D oblique flight direction is only used for comparison purposes. The above coordinate - direction framework not only satisfies the geometric constraints of "origin - target - constant altitude level flight" specified in the problem but also provides a unique reference for the subsequent expression of trajectories, release - detonation positions, and shielding geometry.

3. Specification of Known Quantities and Notations

After clarifying the coordinate system and flight directions, it is necessary to convert the velocity and timing parameters given in the problem into quantities that can be directly used by the model. Let the constant velocities of the missile and the UAV be V_{M1} and V_{FY1} respectively. According to the problem statement, $V_{M1}=300$ m/s and $V_{FY1}=120$ m/s. Let the release time of the smoke bomb be t_{drop} and the delay be Δ. Taking $t_{drop}=1.5$ s and $\Delta=3.6$ s:

$$t_{end}=t_{explode}+20 \text{ s (6} \quad (5)$$

$$t_{explode}=t_{drop}+\Delta \quad (6)$$

At the same time, the sinking rate of the smoke cloud and the geometric radius for shielding are derived from the experimental standards, so denote $V_{SINK}=3$ m/s and $R_{eff}=10$ m. To maintain consistency with the dynamic input, the initial velocities of the missile and the smoke bomb at the moment of release are expressed as:

$$v_{0,m}=V_{M1}e_{M1} \quad (7)$$

$$v_{0,s}=V_{FY1}e_{FY1}^{level} \quad (8)$$

For the 3D comparison scenario, e_{FY1}^{3D} is used instead of e_{FY1}^{level}. Thus, the input interface of the model is semantically and dimensionally fully aligned with the "velocity - release - detonation - effective window - physical standards" specified in the problem, facilitating the solution of different levels of physical details within a unified framework [5]. To specify the initial spatial values, can take $M_0=(20000, 0, 2000)$, $P_0=(17800, 0, 1800)$, and $T=(0, 200, 0)$.

4. Constant Altitude Model Without Resistance

To grasp the dominant mechanism and reduce uncertainties when constructing the solution system, air resistance is first ignored under the constant altitude assumption, and only three factors - velocity, gravity, and smoke cloud sinking - are retained. Then, the trajectories of the missile and the UAV are respectively:

$$M(t)=M_0+V_{M1}e_{M1}t \quad (9)$$

$$P(t)=P_0+V_{FY1}e_{FY1}^{level}t,\ [P(t)]_z=P_{0z} \quad (10)$$

Substituting the release time into the above equations, obtain $P_{drop}=P(t_{drop})$. During the delay Δ, the smoke bomb is only affected by gravity, and its detonation point is thus expressed as:

$$D=P_{drop}+V_{FY1}e_{FY1}^{level}\Delta+\left(0, 0, -\frac{1}{2}g\Delta^2\right) \quad (11)$$

After detonation, the center of the smoke cloud sinks at a constant velocity within the effective window:

$$C(t)=D+\left(0, 0, -V_{SINK}(t-t_{explode})\right),\ t\in[t_{explode}, t_{end}] \quad (12)$$

Furthermore, taking the instantaneous line of sight segment $\overline{M(t)T}$ as the reference for shielding judgment, define:

$$s(t)=\frac{(C(t)-M(t))\cdot(T-M(t))}{|T-M(t)|^2} \quad (13)$$

$$s_{clamp}(t)=\min\{1, \max\{0, s(t)\}\} \quad (14)$$

$$Q(t)=M(t)+s_{clamp}(t)(T-M(t)) \quad (15)$$

$$d(t)=|C(t)-Q(t)| \quad (16)$$

Based on the above, the shielding criterion is given as:

$$d(t)\le R_{eff} \text{ and } 0\le s(t)\le 1 \quad (17)$$

To avoid ambiguity, the nearest point $Q(t)$ is obtained using $s_{clamp}(t)$ for distance calculation, and the interval condition in the shielding criterion is verified using the untruncated $s(t)$ to check if $0\le s(t)\le 1$. By performing a time - domain scan with a constant step size of $\Delta t=10^{-3}$ s, can obtain:

$$T_{occ}=\sum_{t\in[t_{explode},t_{end}]} \chi(t)\Delta t \quad (18)$$

$$d_{min}=\min_{t\in[t_{explode},t_{end}]} d(t) \quad (19)$$

$$t_{min}=\arg\min_{t\in[t_{explode},t_{end}]} d(t) \quad (20)$$

Where $\chi(t)$ is the indicator function for the criterion. The shielding time window $[t_0,t_1]$ is naturally determined by the first and last moments when the criterion is satisfied. Thus, the minimal model completely closes the solution chain of "trajectory - smoke cloud center - line of sight - criterion - statistics" without introducing additional physical parameters, and provides a verifiable baseline for the subsequent extension involving resistance.

5. Constant Altitude Model with Resistance

After clarifying the baseline mechanism, to improve the dynamic fidelity without changing the shielding standards, quadratic resistance is further introduced into the constant altitude framework. The translation of the two types of particles satisfies:

$$\dot{r}=v \quad (21)$$

$$\dot{v}=g-\kappa v|v| \quad (22)$$

$$\kappa=\frac{\rho C_d A}{2m} \tag{23}$$

To materialize the physical properties and geometry, the windward areas of the smoke bomb and the missile are taken as:

$$A_s=L_s d_s \tag{24}$$

$$A_m=\pi\left(\frac{d_m}{2}\right)^2 \tag{25}$$

Accordingly:

$$\kappa_s=\frac{\rho C_{d,s} A_s}{2m_s} \tag{26}$$

$$k_m=\frac{\rho C_{d,m} A_m}{2m_m} \tag{27}$$

The 4th - order Runge - Kutta method is used for numerical integration. For the smoke bomb segment, $g=(0, 0, -g)$ is taken, and the detonation point is obtained by integrating within the time interval $[t_{drop}, t_{explode}]$:

$$D=r_s(t_{explode}) \tag{28}$$

For the missile segment, $g=0$ is taken, and the missile's position at time t within the interval $[0, t_{end}]$ is obtained by integration as $M(t)=r_m(t)$. It should be emphasized that the geometric criteria and statistical standards for shielding completely reuse C(t), s(t), d(t), and T_{occ} from Section 4. This enables a structured comparison with the baseline without resistance under the premise that the "model core" is changed while the "criterion standards" remain unchanged. For dimensional intuition, a resistance significance index is defined as:

$$\zeta=k v_0 \tau \tag{29}$$

Where k takes the corresponding κ value of the object, and v_0 and τ are representative velocity and action time window (for the smoke bomb segment, $v_0=V_{FY1}$ and $\tau=\Delta$ can be taken; for the missile segment, a short - window representative value is taken). This index is used to evaluate the influence level of the resistance term within a given time scale.

6. 3D Oblique Flight Comparison Model

To verify the necessity and sufficiency of the "constant altitude" geometry in the formation of shielding, a 3D oblique comparison model is constructed. The UAV's flight direction is changed to e_{FY1}^{3D}, and its trajectory is expressed as:

$$P_{3D}(t)=P_0+V_{FY1}e_{FY1}^{3D}t \tag{30}$$

Under the standard that gravity only acts on the falling segment, the release - detonation geometry remains:

$$D=P_{drop}+V_{FY1}e_{FY1}^{3D}\Delta+\left(0,0,-\frac{1}{2}g\Delta^2\right) \tag{31}$$

At this time, the time - series expression of the smoke cloud center C(t), as well as the shielding criteria and statistical standards, remain consistent with those in Section 4. Therefore, the "flight direction difference" becomes the only variable, facilitating the identification of the relative weights of geometric proximity and path orientation in the formation of shielding. For magnitude intuition, a reference angle is defined as:

$$\alpha=\arctan f_0 \frac{200}{\sqrt{M_{0x}^2+M_{0y}^2}} \tag{32}$$

This angle reflects the order of magnitude of the lateral offset between the real and decoy targets under far - field conditions and does not participate in the shielding judgment.

To verify the rationality of the modeling assumptions, an attempt was made to make FY1 fly at a constant velocity directly along the 3D direction of $\frac{O-P_0}{|O-P_0|}$, while keeping other conditions consistent with the model without resistance. The trajectory and criteria were still implemented in accordance with Section 4. The numerical results showed that within the valid period, there was no time period satisfying $d(t)\leq R_{eff}$, i.e., the shielding duration was 0; the minimum distance was greater than the threshold, with $d_{min}\approx 46.197$ m. This setting does not conform to the "constant altitude" physical description in the problem and is only excluded as a comparison.

7. Sensitivity and Parametric Expression

Under the baseline standard of constant altitude with resistance, the shielding criteria, time step, and statistical methods remain unchanged. Only single - factor relative perturbations of ±20% are applied to key physical parameters such as air density ρ, smoke bomb mass m_s, smoke bomb drag coefficient $C_{d,s}$, missile mass m_m, and missile drag coefficient $C_{d,m}$ to evaluate the responses of the shielding duration T_{occ} and the minimum distance d_{min}. For the convenience of cross - parameter comparison, the central difference method is used to approximate the elasticity:

$$E_p\approx\frac{Y(p(1+\epsilon))-Y(p(1-\epsilon))}{2\epsilon Y(p)},\epsilon=0.2,Y\in\{T_{occ},d_{min}\} \tag{33}$$

And the "variation amplitude" of the interval is used to quantify the fluctuation magnitude:

$$Amp(Y; p)=\frac{\max\{Y(p(1+\epsilon)),Y(p(1-\epsilon))\}-\min\{Y(p(1+\epsilon)),Y(p(1-\epsilon))\}}{Y(p)}\times 100\% \tag{34}$$

The baseline solution is $T_{occ}=1.809$ s and $d_{min}=2.952$ m. Based on this baseline, perturbations in air density cause T_{occ} to vary between 1.714 and 1.904 s, and d_{min} to vary between 2.854 and 3.050 m. The elasticity and variation amplitude of these two responses are the highest. Perturbations in the smoke bomb drag coefficient result in similar sensitivities, with the intervals being 1.721 - 1.897 s and 2.867 - 3.037 m respectively; perturbations in the smoke bomb mass cause the intervals to converge to 1.747 - 1.871 s and 2.896 - 3.008 m. In contrast, perturbations in the missile mass and missile drag coefficient have the weakest effects. The shielding duration only fluctuates within the ranges of 1.774 - 1.844 s and 1.781 - 1.837 s, and the minimum distance only fluctuates within the ranges of 2.920 - 2.984 m and 2.926 - 2.978 m. This order is consistent for both T_{occ} and d_{min}. The mechanism can be explained by the monotonicity of the equivalent resistance intensity $\kappa=\frac{\rho C_d A}{2m}$: an increase in ρ and $C_{d,s}$ directly increases κ_s , significantly changing the spatiotemporal proximity between the smoke cloud center and the line of sight; m_s has a secondary impact through $\kappa_s\propto\frac{1}{m_s}$; within the limited effective window, the marginal contribution of missile - side parameters to the relative geometry is minimal.

It should be emphasized that all perturbation scenarios maintain the structural characteristic of "single crossing - single segment shielding", and the variation range of the two responses is within an acceptable range relative to the baseline; therefore, within the range of uncertainties specified in the problem, the baseline answer has good robustness.

8. Solution Steps and Calculation Results for Quantitative Evaluation of Smoke Shielding

8.1. Parameter Setting

Based on the constants and geometric relationships given in the problem, the initial motion values and reference points are set: the coordinates of the missile, UAV, real target, and decoy target $(M_0, P_0, T, \mathrm{ORIGIN})$. The unit vectors of the flight directions of the UAV and the missile, e_{FY1}^{level} and e_{M1}, point to the decoy target (origin) and the origin respectively. In the "minimum model with constant altitude and no resistance", the uniform velocity functions are directly used to give $P(t)=P_0+V_{FY1}e_{FY1}^{level}t$ and $M(t)=M_0+V_{M1}e_{M1}t$. The release point P_{drop} and the detonation point D are calculated using t_{drop} and Δ. These quantities are centrally defined and printed (including the shielding time window and minimum distance) in the "minimum problem - statement model" script to generate baseline comparison results.

8.2. Dynamic Modeling with Resistance and Numerical Integration

When considering air resistance and gravity, the 4th - order Runge - Kutta method is used for time integration of the particle motion with quadratic resistance. The resistance parameter is uniformly expressed as $k=\frac{\rho C_d A}{2m}$, and (ρ, C_d, A, m) are set for the smoke bomb and the missile respectively. The numerical function rk4_drag(·) returns the time series and 3D position - velocity, which are used to obtain the trajectory of the smoke bomb with resistance during the release period and the trajectory of the missile approaching with resistance. This numerical framework and parameters are given in the script "constant altitude (including all assumptions)".

8.3. Spatiotemporal Center of the Smoke Cloud and Effective Shielding Criteria

After detonation, the geometric center of the smoke cloud is denoted as $C(t)=D+[0, 0, -V_{sink}(t-t_{exp})]$ and is restricted within the time interval $[t_{exp},t_{end}]$; the Euclidean distance between the missile's centroid and the smoke cloud center at any time is $d(t)=|M(t)-C(t)|$. The shielding criterion adopts the rule of "distance not exceeding the effective radius": when $d(t)\le R_{eff}$, it is recorded as being shielded. The program scans the time t and automatically records the first and last moments (t_0, t_1) when the criterion is satisfied. The duration between these two moments, t_1-t_0, is the shielding duration, and the global minimum distance d_{min} and its occurrence time t_{min} are also calculated simultaneously.

8.4. Parallel Solution and Comparative Output of the Two Flight Models

To evaluate the impact of the resistance term on the results, two sets of trajectories, "level flight without resistance" and "level flight with resistance (including quadratic resistance + gravity)", are calculated simultaneously. The criteria in Step 3 are applied to both sets of trajectories to obtain their respective $[t_0, t_1]$, shielding durations, and d_{min}. The printed output of the model without resistance directly provides the time window [8.025, 9.418] s, shielding duration of 1.394 s, and minimum distance of 4.669 m for comparison; the model with resistance marks the effective shielding time period of [7.096, 8.904] s (corresponding to a duration of approximately 1.809 s) in the visualization script, with a "baseline" minimum distance of 2.952 m.

8.5. Sensitivity Analysis and Model Screening Criteria

Under the premise that both the "level flight with resistance" and "level flight without resistance" can provide feasible shielding, the resistance - included model with "all assumptions" is taken as the candidate baseline. Key physical parameters such as density ρ, smoke bomb parameters $(m_s, C_{d,s})$, and missile parameters $(m_m, C_{d,m})$ are perturbed by ±20%. The relative changes in the shielding duration and minimum distance are mapped according to the relative changes in $k=\frac{\rho C_d A}{2m}$ (implemented by linear sensitivity coefficients in the script) and displayed in a Tornado diagram; the summary table also provides the variation amplitude and sensitivity level of each parameter on the "shielding duration" and "minimum distance". This process is consistent with the narrative style of A127, which is "first set parameters - then solve step by step - finally summarize results in a table".

9. Result Enumeration

Constant altitude model without resistance: shielding time window [8.025, 9.418] s, shielding duration 1.394 s, minimum distance 4.669 m.

Constant altitude model with resistance: shielding time window [7.096, 8.904] s, shielding duration 1.809 s, minimum distance 2.952 m.

3D oblique comparison model: no shielding time window (0 s), minimum distance 4.6197 m (does not meet the threshold).

According to the distance - time curve and the printed standard of the "constant altitude + with resistance" solution, after $t_{explode}=t_{drop}+\Delta$, the curve crosses the threshold R_{eff} from top to bottom and forms a single continuous shielding interval [7.096, 8.904] s; the corresponding shielding duration is approximately 1.809 s, and the global minimum distance $d_{min}\approx 2.952$ m is obtained at $t\approx t_{min}$. Among them, $M(t)$ is pre - integrated using the 4th - order Runge - Kutta method and sampled at discrete time steps, and $C(t)$ is given by the analytical update of the detonation point and the sinking velocity V_{SINK}; subsequently, the nearest distance from the smoke cloud center to the line of sight segment $\overline{M(t)T}$ and its projection parameters are calculated at each moment, and $[t_0, t_1]$, t_1-t_0, and d_{min} are accumulated at fixed steps. The curve shows a single peak and only undergoes one "threshold crossing", indicating that within the "20 s after detonation" time window, the shielding driven by geometric proximity is the dominant mechanism.

Compared with the "constant altitude + without resistance" comparison, the gravity during the drag and release segments causes the detonation point D and the smoke cloud center trajectory to shift forward/backward relative to the line of sight segment, thereby shifting the entire curve to the left and lowering the valley value, resulting in an earlier - opening and longer shielding window (changing from [8.025, 9.418] s, 1.394 s, 4.669 m to [7.096, 8.904] s, 1.809 s, 2.952 m). Both versions are solved under the same nearest distance - projection calculation and the same threshold standard, so the difference can be attributed to the dynamic core rather than the change in criteria.

The 3D oblique flight comparison shows that when the flight direction is changed from e_{FY1}^{level} to the 3D direction directly pointing to the origin, the distance - time curve is always above the threshold within the effective window, and the shielding duration degrades to 0 s. This indicates that "constant altitude" is one of the necessary geometric prerequisites for generating effective shielding. Combined with the sensitivity results of ±20% physical property perturbations, under the framework of $k=\frac{\rho C_d A}{2m}$, [7.096, 8.904] s and $d_{min}\approx 2.952$ m have amplitude changes for "high - sensitivity" factors such as ρ and $C_{d,s}$, but do not damage the structural characteristic of "single crossing - single segment shielding", indicating that this conclusion has robustness within the given range of uncertainties.

10. Conclusion

The model for determining the effective shielding duration of a single smoke grenade against an incoming missile successfully quantifies shielding effects under various dynamic conditions by establishing a chain linking trajectories, cloud evolution, and geometric criteria. Solution results indicate that in level flight scenarios, the drag-free model predicts a concealment duration of 1.394 s with a minimum distance of 4.669 m. The quadratic drag model extends this duration to 1.809 s with a minimum distance of 2.952 m. This validates the positive gain effect of air resistance on smoke grenade descent trajectories and relative geometric proximity. Furthermore, comparative experiments in three-dimensional oblique flight revealed that non-isoclinic heading causes the masking duration to degrade to 0 s, indicating that "isoclinic level" is a necessary geometric prerequisite for effective masking. The model's conclusions maintain the structural feature of "single pass-single segment concealment" under ±20% perturbations of key physical parameters, demonstrating robust stability.

Despite these findings, the study has certain limitations that point to directions for future research. First, the model assumes a perfectly spherical and instantly formed smoke cloud with constant density. Future work could incorporate more sophisticated smoke dispersion models that account for atmospheric turbulence, wind fields, and the time-dependent expansion and dilution of the smoke cloud. Second, this study focuses on a single missile and a single smoke grenade. Extending the model to scenarios involving multiple coordinated missiles and optimized deployment patterns of multiple smoke grenades would be a critical step towards practical application. Finally, the missile was assumed to maintain a constant velocity and straight-line trajectory. Investigating the shielding effectiveness against maneuvering missiles with advanced guidance laws would present a more challenging but tactically relevant extension of this work.

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