

Optimization of Multi UAV Collaborative Interference Strategy Based on 3D Vision Blocking and Improved Genetic Algorithm

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Abstract: A series of mathematical models, from easy to difficult, have been established to optimize the deployment strategy of smoke screen jamming missiles, in order to obtain the longest time for smoke screen jamming missile projection under the same conditions and achieve maximum shielding of incoming missiles. Based on the positional relationship between various objects, the principle of line of sight obstruction between straight lines and curves is applied to determine the optimal value of various factor masking effects; We separately studied the multi scenario optimization problems of single machine single missile, multi machine single missile, single machine multi missile, multi machine multi missile single interference, and multiple interference, and obtained relevant algorithms to solve the optimal solution; By adjusting the optimization parameters and selecting optimization methods, it can be seen that under a certain adversarial approach, setting reasonable drone flight parameters and the timing of smoke screen jamming can greatly increase the probability of enemy missiles being effectively blocked. This article establishes a mathematical model for the occlusion effect of smoke screen interference missiles based on line of sight obstruction. The detection of the missile's line of sight to the target and the occlusion effect of smoke screen cloud clusters are quantified as the intersection problem of line segments and spheres in geometric space. 18 key points are selected from a real target cylinder to determine its probability of being hit. Whether the missile's line of sight to each key point is occluded by the smoke screen cloud cluster is considered as whether the key point is occluded. The simultaneous occlusion of all key points is used as the basis for determining effective occlusion. Numerical simulation is used to calculate the occlusion state over time with a time step of 0.01 seconds. Finally, when the drone FY1 flies at a speed of 120m/s next to the target and is ordered to throw the interference missile within 1.5 seconds, the occlusion state is obtained. When detonating within s, the effective shielding time of the smoke screen interference bomb on missile M1 is 1.38 seconds (occurring within 8.06-9.44 seconds); Visual analysis shows that although the effective period of smoke clouds is as long as 20 seconds, only about 7% of the time can form effective shielding due to the dynamic changes in spatial geometric relationships.

Keywords: Smoke screen interference bomb, Line of sight obstruction, Shielding effect evaluation, Multi-dimensional parameter optimization.

1. Introduction

Smoke screen interference is a defense method that uses manual deployment to produce aerosol clouds of a certain shape through chemical combustion or explosion, blocking the infrared signals of targets in a certain airspace in front of them, thereby interfering with the normal operation of guided weapons[1]. With the development of drones, current military defense systems are using more drones to drop smoke screen jamming shells, using fixed-point throwing and time fuses to achieve a sequence, improving the previous situation where a smoke screen jamming shell needed to consume three to four hundred kilograms or even more to increase costs to just a few hundred kilograms now. The deployment of unmanned aerial vehicles (UAVs) in conjunction with smoke screens has been incorporated into modern air defense and anti missile systems as an important means. Through the collaborative work of multiple UAVs, a continuous smoke screen is formed to block incoming missiles from the target[2].

The models and algorithms proposed in this article are based on certain mathematical theories and physical

principles, which can accurately describe the dynamic characteristics and effectiveness evaluation indicators of the smoke screen jamming missile protection system[3]. The optimization results show that, based on the reasonable setting of drone flight parameters and smoke screen jamming missile throwing strategies, the effectiveness of missile protection against incoming missiles can be effectively enhanced; At the same time, the model still needs further improvement, such as not considering the influence of external wind speed and the uneven distribution of smoke cloud density, which need to be taken into account in practical use; In addition, for high-dimensional optimization problems, the computation time will still be relatively long, which can be improved through algorithm and optimization of computing resources; Finally, further improvements will be made based on a more diverse battlefield environment, different types of incoming weapons, and more flexible drone maneuvering methods to make it more suitable for practical combat needs.

2. Mathematical model of smoke screen interference projectile shielding effect based on line of sight obstruction

Assuming a missile M1 flies from its initial position (20000, 0, 2000) at a speed of 300 m/s towards the origin (0, 0, 0), which is a false target[4]. There is a real target located at (0, 200, 0), which is a cylinder with a base radius of 7 meters and a height of 10 meters. A drone FY1 flies towards a false target direction from its initial position (17800, 0, 1800) at a speed of 120 m/s and an equal altitude. The drone releases smoke screen jamming shells 1.5 seconds after receiving the mission. After the smoke screen jamming shells are released, they inherit the speed of the drone in the horizontal direction and perform uniform acceleration motion in the vertical direction due to gravity. The smoke screen interference bomb detonated 3.6 seconds after being dropped, forming a spherical smoke screen cloud with a radius of 10 meters. The cloud sinks at a constant speed of 3 m/s and is effective within 20 seconds. The objective of this study is to establish a mathematical model to calculate the effective shielding time of smoke screen interference missiles against missile M1, that is, the total length of time during missile flight when smoke cloud clusters effectively block the line of sight from the missile to the real target.

2.1. Analysis of the Approach for Evaluating the Shielding Effect of Smoke Screen Interference Bullets

In order to quantitatively evaluate the effective shielding degree of smoke screen interference missile on missile M1, a mathematical model based on the principle of line of sight shielding can be constructed to calculate whether the smoke screen cloud can effectively shield the line of sight connection between the missile and the real target; The specific criteria for determining whether effective masking can be achieved are set as follows: when the smoke cloud is located on the line of sight path between the missile and the real target and can effectively absorb/scatter/reflect signals, it can be considered as achieving effective masking. Considering that missiles mainly rely on direct line of sight or receiving detection signals from targeted targets for attack in practice, the physical meaning of this criterion is to indicate whether a high-density smoke cloud can be used to block the relative direct view channel between the missile and the real target. In addition, considering that the model used in this article may have some errors, it cannot completely and effectively mask all line of sight segments. Instead, it can only mask the vast majority of line of sight segments. Therefore, if a line of sight segment pointing from the emission point to any point on the cylindrical surface is not obscured, it will also be considered as not having effective masking. Similarly, just like the mathematical model designed in this article, real targets other than cylindrical shapes are also situations that need to be considered.

In this problem, this article faces the challenge of calculating the motion trajectories of multiple dynamic targets: missiles flying towards false targets at a certain speed, drones flying towards false targets at equal altitudes, smoke screen interference bombs being thrown by gravity after being deployed, and smoke screen cloud clusters sinking at a constant speed after formation. These dynamic elements

cause the occlusion effect to constantly change over time, requiring us to establish an accurate spatiotemporal relationship model to evaluate the dynamic changes in the occlusion state of the line of sight over the entire time range. It should be noted that due to the constant altitude flight of the drone, its flight trajectory remains constant in the vertical direction and only changes position in the horizontal plane. This constraint condition needs to be specifically considered in the model. Meanwhile, as a cylinder with a certain volume, different points on the surface of the real target may be obscured or exposed at different times. Therefore, it is necessary to comprehensively consider the masking status of multiple key points. Only when all key points are masked can it be determined as effective masking.

2.2. Establishment of mathematical model for dynamic occlusion of line of sight

Based on the above analysis, this article establishes a complete mathematical model for dynamic line of sight occlusion in three-dimensional space. Firstly, we define a three-dimensional Cartesian coordinate system with the false target position as the origin, the ground as the horizontal plane (i.e. xy plane), and the vertical upward direction as the positive z-axis direction. In this coordinate system, this article can accurately describe the positions and movements of all relevant entities.

The initial position vector of missile M1 is defined as $\vec{r}_{M1}(0) = (x_{M1_0}, y_{M1_0}, z_{M1_0})$, and its flight direction is the unit vector pointing towards the false target (origin), which can be expressed as:

$$\vec{e}_{M1} = \frac{\vec{0} - \vec{r}_{M1}(0)}{|\vec{0} - \vec{r}_{M1}(0)|} = \frac{(0,0,0) - (x_{M1_0}, y_{M1_0}, z_{M1_0})}{\sqrt{x_{M1_0}^2 + y_{M1_0}^2 + z_{M1_0}^2}} \quad (1)$$

$\vec{0} = (0,0,0)$ represents the position vector of the false target. With the initial position and flight direction of the missile, this article can use parameter equations to describe the position of missile M1 at any time:

$$\vec{r}_{M1}(t) = \vec{r}_{M1}(0) + v_{M1} \cdot t \cdot \vec{e}_{M1} \quad (2)$$

v_{M1} is the flight speed of the missile.

Next, it is necessary to determine the motion trajectory of the drone FY1. The initial position vector of the drone is $\vec{r}_{FY1}(0) = (x_{FY1_0}, y_{FY1_0}, z_{FY1_0})$. Since the drone is flying at an equal altitude, its flight direction unit vector only has a horizontal component, which can be expressed as:

$$\vec{e}_{FY1} = (-1, 0, 0) \quad (3)$$

Therefore, the position of drone FY1 at any given time is:

$$\vec{r}_{FY1}(t) = \vec{r}_{FY1}(0) + v_{FY1} \cdot t \cdot \vec{e}_{FY1} \quad (4)$$

v_{FY1} is the flight speed of the drone.

The drone drops smoke screen jamming bombs t_{release} seconds after receiving the mission, and the drop location is $\vec{r}_{FY1}(t_{\text{release}})$. After the smoke screen jamming bomb is deployed, it inherits the speed of the drone horizontally and accelerates vertically due to the influence of gravity. Assuming that the initial velocity of the smoke screen jamming projectile during deployment is the same as that of the drone, the position of $t' = t - t_{\text{release}}$ (where $t \geq t_{\text{release}}$) at any time after deployment can be expressed as:

$$\vec{r}_s(t) = \vec{r}_{FY1}(t_{\text{release}}) + (t - t_{\text{release}}) \cdot v_{FY1} \cdot \vec{e}_{FY1} - \frac{1}{2} g(t - t_{\text{release}})^2 \cdot \vec{k} \quad (5)$$

Where $\vec{k} = (0,0,1)$ is the vertical upward unit vector and g is the gravitational acceleration.

The smoke screen interference bomb detonates within t_{fall} seconds after deployment, with the detonation time being

$t_{explosion} = t_{release} + t_{fall}$. At this time, the position of the smoke screen interference bomb is $\vec{r}_S(t_{explosion})$. After the smoke screen interferes and explodes, a spherical cloud cluster is formed, which sinks at a constant speed at v_{sink} . The center of the cloud cluster at any time t (including $t \geq t_{explosion}$) is:

$$\vec{r}_C(t) = \vec{r}_S(t_{explosion}) - v_{sink}(t - t_{explosion}) \cdot \vec{k} \quad (6)$$

This chapter requires determining the key point positions on the real target cylinder. The center position of the bottom surface of the real target is $\vec{T}_{base} = (x_T, y_T, z_T)$, the radius of the bottom surface of the cylinder is $R_{cylinder}$, and the height is $H_{cylinder}$. In order to comprehensively evaluate the effect

$$\vec{P}_{2+n+j} = \vec{T}_{base} + R_{cylinder} \cdot (\cos(\frac{2\pi(j-1)}{n}), \sin(\frac{2\pi(j-1)}{n}), 0) + (0, 0, H_{cylinder}) \quad (10)$$

With the location of the missile, the position of the smoke cloud, and the key points on the real target, it is possible to determine whether the line of sight between the missile and each key point is obscured by the smoke cloud. This problem can be transformed into a geometric problem of determining whether a line segment intersects with a sphere.

Given the missile position $\vec{r}_{M1}(t)$, key point position $\vec{P}_j$, cloud center position $\vec{r}_C(t)$, and radius R_{cloud} , we need to determine whether the line segment $\vec{r}_{M1}(t) \vec{P}_j$ intersects with the sphere $S(\vec{r}_C(t), R_{cloud})$. The condition for a line segment to intersect with a sphere is that there is a point $\vec{Q}$ on the line segment that causes $|\vec{Q} - \vec{r}_C(t)| \leq R_{cloud}$.

To mathematically determine whether a line segment intersects with a sphere (note that this is a line segment, not a straight line), use a parametric equation to represent any point on the line segment:

$$\vec{Q}(\lambda) = \vec{r}_{M1}(t) + \lambda \cdot (\vec{P}_j - \vec{r}_{M1}(t)), \quad \lambda \in [0, 1] \quad (11)$$

Substitute this point into the sphere equation:

$$|\vec{Q}(\lambda) - \vec{r}_C(t)|^2 = R_{cloud}^2 \quad (12)$$

Expand to obtain:

$$|\vec{r}_{M1}(t) + \lambda \cdot (\vec{P}_j - \vec{r}_{M1}(t)) - \vec{r}_C(t)|^2 = R_{cloud}^2 \quad (13)$$

Let $\vec{v} = \vec{P}_j - \vec{r}_{M1}(t)$ (direction vector of line segment), $\vec{w} = \vec{r}_{M1}(t) - \vec{r}_C(t)$ (vector from missile position to cloud center), the above equation can be simplified as:

$$|\vec{w} + \lambda \cdot \vec{v}|^2 = R_{cloud}^2 \quad (14)$$

Further development:

$$(\vec{w} + \lambda \cdot \vec{v}) \cdot (\vec{w} + \lambda \cdot \vec{v}) = R_{cloud}^2 \quad (15)$$

$$\vec{w} \cdot \vec{w} + 2\lambda \cdot \vec{v} \cdot \vec{w} + \lambda^2 \cdot \vec{v} \cdot \vec{v} = R_{cloud}^2 \quad (16)$$

This is a quadratic equation about λ :

$$a\lambda^2 + b\lambda + c = 0 \quad (17)$$

Among which:

$$a = \vec{v} \cdot \vec{v} = |\vec{v}|^2 \quad (18)$$

$$b = 2\vec{v} \cdot \vec{w} \quad (19)$$

$$c = \vec{w} \cdot \vec{w} - R_{cloud}^2 = |\vec{w}|^2 - R_{cloud}^2 \quad (20)$$

Judging whether the line segment intersects with the sphere is equivalent to determining whether the quadratic equation has a solution in the interval $[0, 1]$. The discriminant for a quadratic equation is $\Delta = b^2 - 4ac$.

If $\Delta < 0$, then the equation has no real number solution and the line segment does not intersect with the sphere;

If $\Delta \geq 0$, then the equation has a real number solution, and the solution is $\lambda_{1,2} = \frac{-b \pm \sqrt{\Delta}}{2a}$. Only when $\lambda_1 \in [0, 1]$ or $\lambda_2 \in$

of line of sight occlusion, we need to select a series of representative key points on the cylinder, including the center of the bottom surface, the center of the top surface, and multiple points evenly distributed on the circumference of the bottom and top surfaces. Assuming we select n points on each of the bottom and top circumferences, the set of keypoints can be represented as:

Bottom center

$$\vec{P}_1 = \vec{T}_{base} \quad (7)$$

Top center

$$\vec{P}_2 = \vec{T}_{base} + (0, 0, H_{cylinder}) \quad (8)$$

For point $j = 1, 2, \dots, n$ on the bottom circumference:

$$\vec{P}_{2+j} = \vec{T}_{base} + R_{cylinder} \cdot (\cos(\frac{2\pi(j-1)}{n}), \sin(\frac{2\pi(j-1)}{n}), 0) \quad (9)$$

For point $j = 1, 2, \dots, n$ on the top circumference:

$[0, 1]$, the line segment intersects with the sphere.

By calculating whether the line of sight between the missile and each key point is obstructed by smoke clouds, it is determined at each moment whether effective obstruction has been formed. Effective occlusion is considered only when the line of sight of all key points is obscured, that is, when all line segments intersect the sphere.

In order to calculate the total duration of effective masking, it is necessary to gradually check the masking status at each moment throughout the entire time range (from the formation time $t_{explosion}$ of the cloud cluster to the disappearance time $t_{explosion} + t_{lifetime}$ of the cloud cluster, where $t_{lifetime}$ is the effective duration of the cloud cluster). The total duration of effective masking is equal to the cumulative time of all effective masking moments.

2.3. Numerical solution steps for dynamic occlusion model of line of sight

Based on the above mathematical model, numerical methods are used to solve the effective shielding time of smoke screen interference missile on missile M1[5]. The specific solving steps are as follows:

Firstly, determine the appropriate time step Δt and discretize the entire analysis time range $[0, t_{end}]$ into a finite number of time points $\{t_i = i \cdot \Delta t, i = 0, 1, 2, \dots, N\}$, where $N = \lceil t_{end}/\Delta t \rceil$. The selection of time step requires a balance between computational accuracy and efficiency, and should generally be less than the characteristic time of the fastest changing process in the system. In this article, considering the high-speed movement of missiles and the sinking speed of smoke clouds, the time step can be selected between 0.01 seconds and 0.1 seconds.

Next, calculate and evaluate each discrete time point t_i . For each time point, first calculate the position $\vec{r}_{M1}(t_i)$ of missile M1. If the current time t_i is before the formation of the smoke cloud (i.e. $t_i < t_{explosion}$) or exceeds the effective period of the cloud (i.e. $t_i > t_{explosion} + t_{lifetime}$), effective shielding cannot be formed at that time. Otherwise, it is necessary to calculate the position $\vec{r}_C(t_i)$ of the center of the smoke cloud cluster and determine whether the line of sight between the missile and each key point is obscured by the cloud cluster.

For each keypoint $\vec{P}_j$, calculate whether the line segment $\vec{r}_{M1}(t_i) \vec{P}_j$ intersects with the sphere $S(\vec{r}_C(t_i), R_{cloud})$.

Firstly, calculate the direction vector $\vec{v} = \vec{P}_j - \vec{r}_{M1}(t_i)$ of the line segment and the vector $\vec{w} = \vec{r}_{M1}(t_i) - \vec{r}_C(t_i)$ from the missile position to the center of the cloud cluster. Then, calculate the coefficients of the quadratic equation: $a = |\vec{v}|^2$, $b = 2\vec{v} \cdot \vec{w}$, $c = |\vec{w}|^2 - R_{cloud}^2$ and the discriminant $\Delta = b^2 - 4ac$.

If $\Delta < 0$, the line segment does not intersect with the sphere, and the line of sight of the key point is not obscured;

If $\Delta \geq 0$, calculate the solution $\lambda_{1,2} = \frac{-b \pm \sqrt{\Delta}}{2a}$ of the quadratic equation. If $\lambda \in [0,1]$ exists such that $\lambda = \lambda_1$ or $\lambda = \lambda_2$, then the line segment intersects the sphere and the line of sight of the key point is obscured.

At a time point t_i , if the line of sight of all key points is obscured, that is, all line segments intersect with the sphere, it is considered that effective occlusion has been formed at that time, and the occlusion state at that time is marked as 1; Otherwise, mark it as 0. After traversing all time points, a masking state sequence $\{s_i, i = 0, 1, 2, \dots, N\}$ is obtained, where $s_i \in \{0, 1\}$ represents the masking state at time t_i .

The total duration of effective masking can be calculated by accumulating the time steps corresponding to all masking state 1 time points: $T_{effective} = \sum_{i=0}^N s_i \cdot \Delta t$. In addition, by analyzing the changes in the masking state sequence, continuous effective masking time intervals can be identified, that is, finding all times t_i that satisfy $s_i = 1$ and $s_{i-1} = 0$ as the starting time of effective masking, and all times that satisfy $s_i = 1$ and $s_{i+1} = 0$ as the ending time of effective masking, thus obtaining a series of effective masking time intervals $\{[t_{start,k}, t_{end,k}], k = 1, 2, \dots, K\}$, where K is the total number of effective masking intervals. The duration of each interval is $t_{end,k} - t_{start,k}$, and the total duration of effective masking can also be expressed as the sum of the durations of all intervals: $T_{effective} = \sum_{k=1}^K (t_{end,k} - t_{start,k})$.

In addition, more refined evaluation indicators can be introduced, such as the masking rate distribution of key points. For each key point $\vec{P}_j$, its masking rate can be defined as the proportion of the time the point is masked to the effective period of the smoke cloud: $R_j = \frac{\sum_{i=0}^N s_{i,j} \cdot \Delta t}{t_{lifetime}}$, where $s_{i,j} \in \{0, 1\}$

represents the masking state of the t_i key point $\vec{P}_j$ at time. By analyzing the distribution of masking rates at different key points, we can gain a deeper understanding of the masking effect of smoke screen jamming bullets and the vulnerable areas of targets.

Finally, in order to verify the effectiveness and reliability of the model, a visualization method was used to visually demonstrate the shielding effect of smoke screen interference

bullets. By drawing missile trajectories, smoke cloud locations, real target shapes, and line of sight occlusion states in three-dimensional space, we can intuitively observe and analyze the protective effect of smoke interference missiles. In addition, it is possible to plot the temporal variation curve of the occlusion state and the distribution map of the occlusion rate of key points, providing richer information support for the interpretation and application of the model results.

This study established a mathematical model for dynamic occlusion of line of sight in three-dimensional space, combined with numerical methods, to quantitatively evaluate the protective effect of smoke screen interference bullets. This model not only considers the spatiotemporal relationship of each dynamic element in the system, but also achieves a comprehensive evaluation of the overall masking effect of the real target through key point sampling and line of sight masking judgment. Through this model, we can calculate the effective shielding time of smoke screen jamming shells on missile M1, providing quantitative basis for the tactical application and protection system optimization of smoke screen jamming shells.

2.4. Analysis and visualization of the solution results of the dynamic occlusion model for line of sight

Based on the established mathematical model of dynamic occlusion of the line of sight, a comprehensive quantitative analysis and visualization of the occlusion effect of smoke screen jamming missiles were carried out through numerical calculation methods to intuitively demonstrate the dynamic changes of the line of sight occlusion effect of smoke screen jamming missiles on missile M1 over time, and to deeply evaluate the temporal and spatial distribution characteristics of the occlusion effect from multiple dimensions. By constructing a numerical calculation framework based on MATLAB, we have achieved high-precision calculation and multi angle visualization of missile trajectories, smoke cloud positions, and line of sight occlusion states, enabling clear presentation and analysis of complex three-dimensional dynamic occlusion processes. The calculation results not only include the time interval and total duration of effective masking, but also the masking statistical data of each key point on the target cylinder, providing a solid data foundation for the comprehensive evaluation of the masking effect of smoke screen interference bombs. Three dimensional visualization of the trajectory of missile M1 and the line of sight occlusion effect of smoke screen interference missiles.

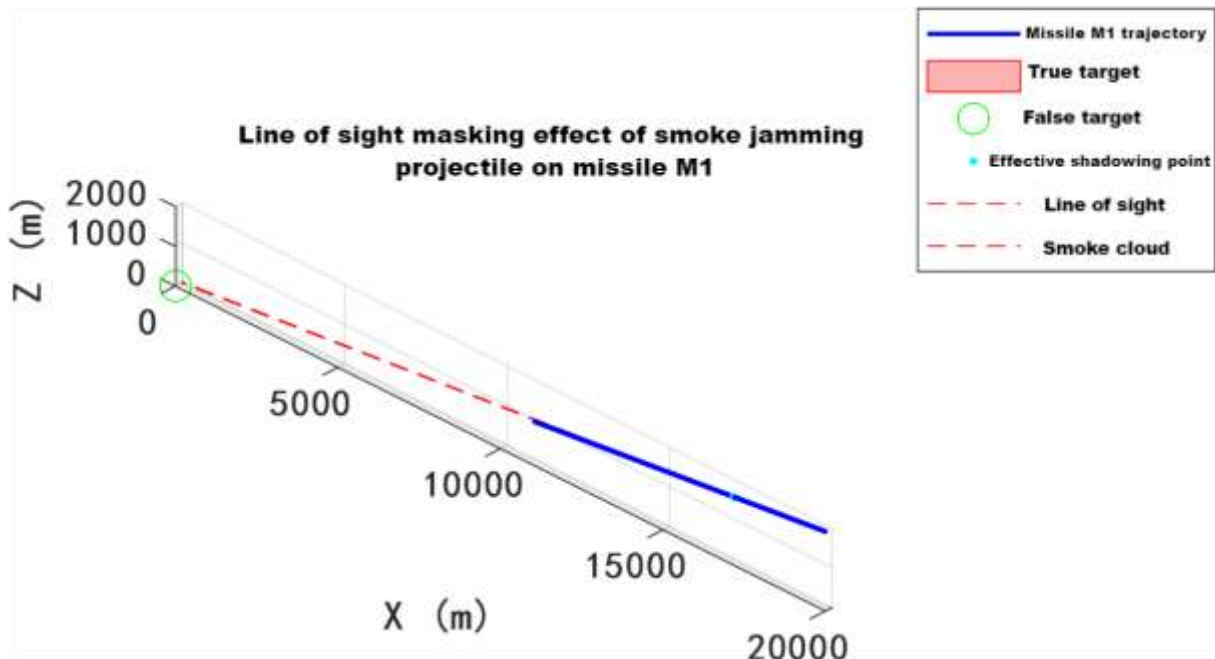


Figure 1: Three dimensional visualization of line of sight occlusion

As shown in Figure 1, the trajectory of missile M1 from its initial position towards a false target (blue line segment), the position of the real target (red rectangular area), the position of the false target (green circle), as well as the effective masking point (blue dot) and line of sight formed at a certain moment (red dashed line). This 3D visualization intuitively displays the spatial relationship between the missile and the target, as well as the occlusion effect of smoke clouds on the line of sight. In the figure, the flight trajectory of the missile extends from a high point on the right to a low point on the left, towards the direction of the false target, while the smoke cloud is located in the spatial position between the missile and

the real target, forming an effective line of sight obstruction. Although only the static occlusion state at a specific moment is shown in the figure, through this visualization, we can intuitively understand the working principle and protection mechanism of the smoke screen jamming missile, that is, by forming an occlusion area between the missile and the real target, it blocks the missile's line of sight detection of the real target.

From the visualization of the effective shielding state of missile M1 over time by the smoke screen jamming missile (as shown in Figure 2), we can clearly see the process of the effective shielding state changing over time.

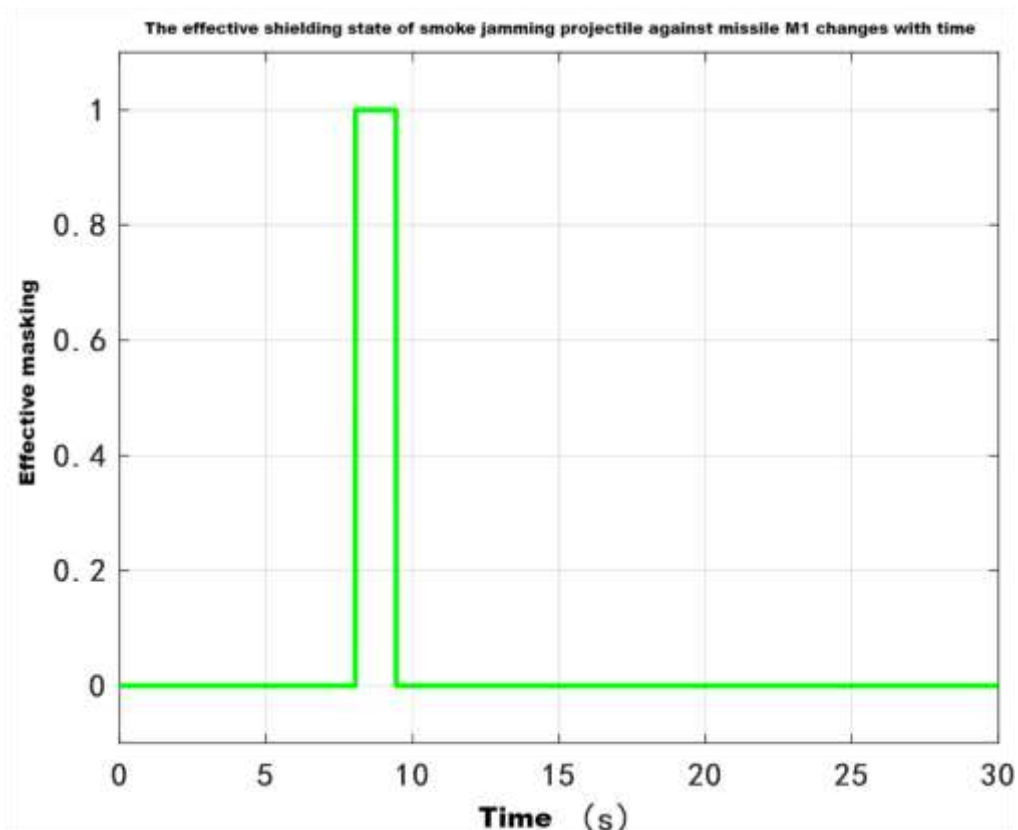


Figure 2: Visualization of the effective masking state over time

This graph shows the variation curve of the effective masking state (with values of 0 or 1) over time throughout the entire analysis time range (0-30 seconds). Based on the calculated data, we found that the smoke screen jamming missile caused a continuous effective shielding time interval for missile M1, from 8.06 seconds to 9.44 seconds, with a duration of 1.38 seconds. This time interval is clearly represented by a green vertical line segment in the graph, indicating that during this time period, the smoke cloud successfully obscured all the line of sight from the missile to

the real target. Outside of this time interval, the values of the effective shielding state are all 0, indicating that no effective shielding protection has been formed. This result indicates that although the effective duration of the smoke cloud cluster is as long as 20 seconds, the actual time for effective shielding to form due to the relative motion of missiles, cloud clusters, and targets only accounts for a small part of the cloud cluster's lifespan, reflecting the time limitation of the smoke interference bomb protection effect.

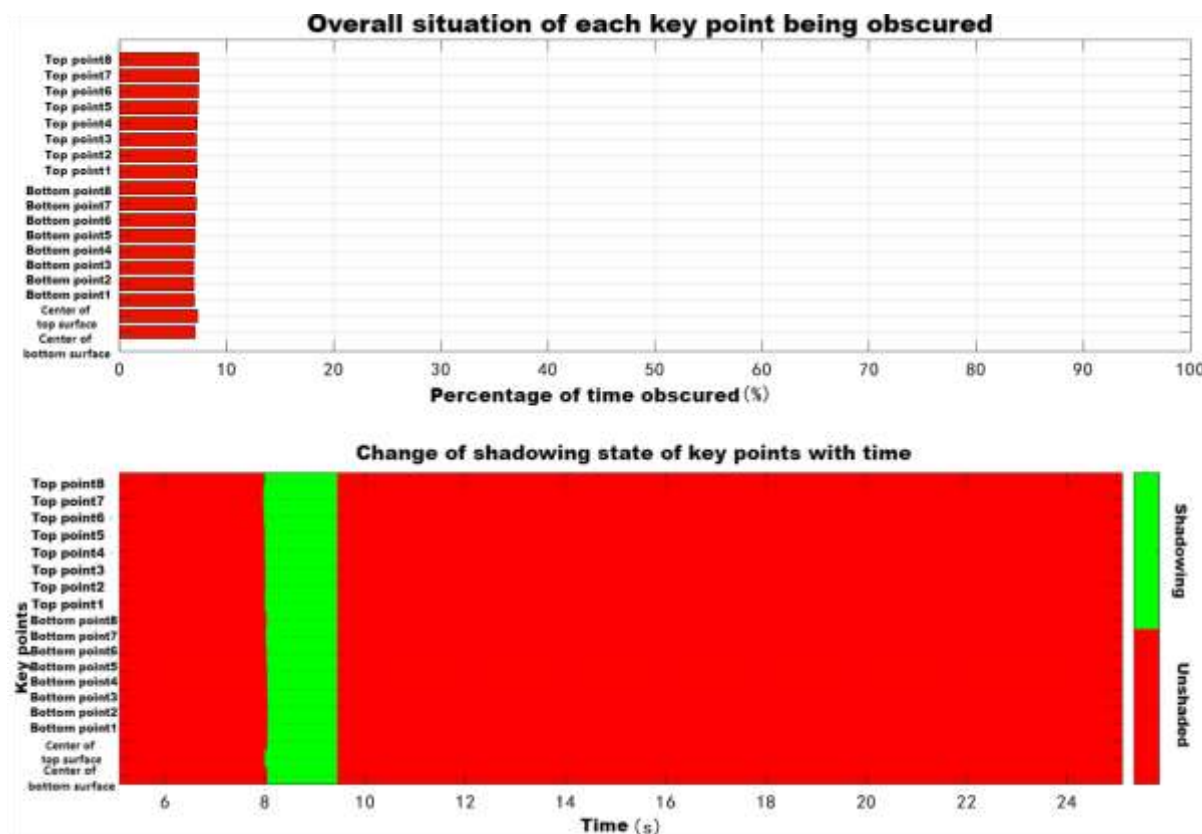


Figure 3: Changes in shielding points over time

Key point masking statistics for Figure 3: First masking (s), last masking (s), masking duration (s), masking percentage (%), bottom center 8.04 9.44 1.41 7.05, top center 7.99 9.44 1.46 7.30, bottom point 1 8.05 9.44 1.40 7.00, bottom point 2 8.06 9.44 1.39 6.95, bottom point 3 8.06 9.44 1.39 6.95, bottom point 4 8.05 9.44 1.40 7.00, bottom point 5 8.04 9.44 1.41 7.05, bottom point 6 8.03 9.44 1.42 7.10, bottom point 7 8.02 9.44 1.43 7.15, bottom point 8 8.03 9.44 1.42 7.10, Top Point 1 8.00 9.44 1.45 7.25, Top Point 2 8.01 9.44 1.44 7.20, Top Point 3 8.01 9.44 1.44 7.20, Top Point 4 8.00 9.44 1.45 7.25, Top Point 5 7.99 9.44 1.46 7.30, Top Point 6 7.98 9.44 1.47 7.35, Top Point 7 7.97 9.44 1.48 7.40, Top Point 8 7.98 9.44 1.47 7.35.

Further analysis of the key point masking statistical data revealed that there were certain differences in masking time among the 18 key points on the target cylinder, including the bottom center, top center, and 8 points on each of the bottom and top circumferences. The key points on the top surface are generally obscured earlier and for a longer period of time than those on the bottom surface. For example, the first masking time of the top center is 7.99 seconds, while the first masking time of the bottom center is 8.04 seconds; The shielding duration of top point 7 is the longest, reaching 1.48 seconds,

while the shielding duration of bottom points 2 and 3 is the shortest, only 1.39 seconds. This difference reflects the spatial relationship between the smoke cloud cluster and different parts of the target, with the top point being more easily obscured by the smoke cloud cluster above due to its higher distance from the ground. However, it is worth noting that the final masking time for all key points is the same, which is 9.44 seconds. This indicates that at the end of masking, the geometric relationship between the entire smoke cloud and the line of sight has changed, resulting in all lines of sight being exposed simultaneously.

From the perspective of occlusion percentage, the occlusion percentage of each key point ranges from 6.95% to 7.40%, with relatively small differences, and the average occlusion percentage is about 7.17%. This data indicates that compared to the entire effective period of the smoke cloud cluster (20 seconds), the proportion of effective shielding time is relatively low, reflecting that under the current parameter settings, the overall protective effect of the smoke interference bomb is relatively limited. This result suggests that in order to improve the protective effect of smoke screen interference grenades, it is necessary to optimize the timing and location of deployment, or increase the number of

deployment to extend the effective shielding time.

Based on the calculation results and visualization analysis, the following key findings have been summarized: firstly, smoke screen jamming missiles can indeed form effective occlusion of the missile's line of sight within a specific time period, but the effective occlusion time is relatively short (1.38 seconds in this example), which may be related to the high-speed motion of the missile and the position and motion characteristics of the smoke screen cloud cluster; Secondly, there are certain differences in the masking time of different parts (key points) on the target, reflecting the complexity of line of sight masking in three-dimensional space; Finally, there is a significant difference between the effective period of the smoke cloud cluster (20 seconds) and the actual time it takes to form effective cover (1.38 seconds), indicating that there is still room for improvement in the efficiency of using smoke interference bombs.

Through the detailed analysis and visualization of the solution results, not only has the effectiveness of the mathematical model for dynamic occlusion of the line of sight been verified, but a deeper understanding of the protective effect of smoke screen interference bullets has also been obtained. These analysis results have important reference value for optimizing the use strategy of smoke screen jamming bombs, improving the effectiveness of protection systems, and providing quantitative basis for combat decision-making. Based on this model, future research can further explore the influence of different parameters (such as launch time, cloud size, sinking speed, etc.) on the shielding effect, as well as the optimization strategy for the collaborative use of multiple smoke interfering bombs, so as to improve the overall protection effect.

3. Conclusions

A complete three-dimensional dynamic line of sight occlusion judgment mechanism was constructed based on the mathematical model of the occlusion effect of the smoke

screen interference bomb based on line of sight obstruction. By accurately quantifying the spatiotemporal relationship between the missile, target, and smoke cloud cluster, the quantitative evaluation of the occlusion effect was achieved, providing a foundation for the optimization of subsequent problems. This model uses keypoint sampling method to represent the geometric characteristics of real targets, transforming complex 3D occlusion problems into geometric problems where multiple line segments intersect with spheres. This not only simplifies the computational complexity but also preserves the physical essence of the problem, accurately reflecting the actual protective effect of smoke screen interference bombs. This model can be extended to other scenarios involving dynamic line of sight occlusion, such as military camouflage, radar interference, communication blockage, etc. By adjusting the target geometry, interference medium characteristics, and motion parameters, the effectiveness of different types of interference methods can be evaluated, providing theoretical basis for the design of various protection systems.

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