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Jamming Missile Deployment Strategy Based on Simulated Annealing Algorithm and Exhaustive Search Method

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Abstract: To enhance the battlefield survivability of personnel and equipment, smoke jamming shells have become one of the focuses of war preparedness research and development in various countries. Based on mechanism analysis at the kinematic level, simulated annealing algorithm under multi-round cyclic mechanism, and exhaustive method, this paper studies the deployment strategy of smoke jamming shells. Based on the motion models of jamming shells, cloud clusters, and missiles, this paper constructs a single-objective optimization mathematical function with the longest effective shielding time as the optimization goal. To obtain more accurate calculation results, this paper adopts the simulated annealing algorithm, which can achieve autonomous multi-round loop functionality, and ultimately derives the optimal effective shielding time.

Keywords: Kinematics equation, simulated annealing algorithm, multi-round loop mechanism, exhaustive search method.

1. Introduction

A smoke jamming shell is a type of ammunition that utilizes explosion or combustion to form smoke or aerosol clouds, thereby obscuring or jamming the target area, and further blocking the enemy's visual observation and even the operation of detection equipment[1]. With the continuous advancement of technology, the methods of deploying smoke jamming shells have gradually become diversified. Among these deployment strategies, the focus of this paper is on the precise deployment strategy of jamming shells, which involves accurately deploying the jamming shells through a deployment device to ensure that they detonate at a designated location[2].

Chaff corridor deployment for unmanned combat aerial vehicles (UCAVs) proposed a time-slotted optimization algorithm that minimizes chaff usage while delaying enemy radar detection[3]. By modeling the probability of target discovery as a function of chaff density and deployment intervals, the algorithm achieved a 30% reduction in resource consumption compared to static strategies[4]. Similarly, a mathematical modeling competition analyzed smoke munition deployment by drones against hypersonic missiles, demonstrating that a 3.6-second delay between release and detonation maximizes coverage of the missile’s trajectory[5]. These findings underscore the importance of temporal precision in neutralizing high-speed threats. A genetic algorithm was also used to optimize flight paths, speeds, and detonation points, achieving a 28% increase in cumulative shielding time compared to manual planning[6].

This paper uses a kinematic model to analyze the mechanism of unmanned aerial vehicles dropping jamming missiles and missiles flying towards false targets, and calculates how long the jamming missiles can provide effective shielding for real targets during this process.

2. Preliminary

2.1. Simulated Annealing Algorithm

Simulated Annealing (SA) is a probabilistic global optimization technique inspired by the annealing process in metallurgy, where a material is heated and then slowly cooled to reduce defects and achieve a low-energy crystalline state[7]. Introduced by Kirkpatrick et al. (1983), SA extends this concept to solve complex combinatorial and continuous optimization problems by escaping local optima through controlled randomness. SA has been successfully applied in diverse fields, such as traveling salesman problems (TSP), VLSI design, protein folding prediction, and machine learning hyperparameter tuning. Recent advancements include hybrid approaches combining SA with genetic algorithms or particle swarm optimization to enhance convergence speed.

2.2. Assumption

(1) Assuming that the smoke screen interference bomb ignores air resistance during flight.

(2) Assuming that the spherical smoke cloud is an ideal uniform sphere, it will not deform during the sinking process.

(3) Assuming the true target is a rigid cylinder without deformation.

(4)Assuming that the drone carries three jamming shells directly during mission execution, to avoid situations where bombs need to be dropped but ammunition is insufficient.

2.3. Notations

The symbols used in the paper are listed in Table 1.

Table 1. Notations

Symbols	Notation	Unit
d	The distance from the center of the smoke screen to the line connecting the missile and the real target	m
t	Total effective shielding duration	s
θ	Angle between drone and surface	∘
g	Acceleration due to gravity	m/s^2
v_d	The speed of the missile	m/s
v_t	The speed at which the cloud cluster descends	m/s
P	Acceptance probability of new solutions in simulated annealing algorithm	%

3. Effective shielding

3.1. The definition of effective shielding

If all the connections between the missile and the true target cylinder pass through the range of the cloud center, it is considered effective shielding. But if the missile has already passed through the cloud cluster, even if all the reverse extension lines connecting the missile and the cylinder also pass through the center of the cloud cluster, it will not be considered as effective shielding. This article considers the entire connection between the missile and the real target passing through the center range of the cloud cluster as effective shielding[8]. Therefore, to eliminate the influence of deformation between the cloud cluster and the cylinder on the calculation process, this article assumes that the spherical smoke cloud cluster is an ideal sphere and will not deform during the sinking process; Assuming the true target is a rigid cylinder without deformation.

$$\begin{cases} x_1 = 17800 - v_f(1.5+3.6) \\ y_1 = 0 \\ z_1 = 1800 - \dfrac{3.6^2}{2} g \end{cases} \tag{1}$$

and

$$\begin{cases} \tan\theta = \dfrac{20000}{2000} \\ t = t_1 + (1.5+3.6) \\ x_2 = \cos\theta\left(\sqrt{20000^2+2000^2} - v_d t\right) \\ y_2 = 0 \\ z_2 = \sin\theta\left(\sqrt{20000^2+2000^2} - v_d t\right) \end{cases} \tag{2}$$

In order to verify whether it is necessary to consider whether the cloud cluster lands before forming effective shielding or the missile will explode before the cloud cluster forms effective shielding when calculating the effective shielding duration, this paper calculates the final height of the cloud cluster and the time for the missile to hit the false target through formulas (3) and (4), respectively.

$$z_t = 1800 - \frac{1}{2} g(1.5+3.6)^2 - v_t t_{yo} \tag{3}$$

$$t_{da} = \frac{\sqrt{20000^2+2000^2}}{v_d} \tag{4}$$

3.2. Solutions of coordinates

By using formulas (3) and (4), this article calculates the final height of the cloud cluster at the end of the effective time, and the motion time of the missile hitting the false target, which proves that there is no need to consider the early landing of the cloud cluster or the early impact of the missile on the false target when calculating the effective shielding time.

3.3. Drone positions' calculation

This article still assumes that the interference bomb ignores air resistance during flight, and then calculates the real-time position of the detonation point through formula (5). After the interference and explosion, a spherical smoke cloud will form, and the cloud will gradually sink over time[9]. Therefore, the coordinates of the cloud will still be consistent with the coordinates of the explosion point, except that the coordinates are constantly decreasing. Therefore, this article calculates the real-time position of the cloud center based on formula (6).

$$\begin{cases} x_7 = 17800 - v_1\cos\beta t_2 - v_1\cos\beta t_3 \\ y_7 = v_1\sin\beta t_2 + v_1\sin\beta t_3 \\ z_7 = 1800 - \dfrac{1}{2} g t_3{}^2 \end{cases} \tag{5}$$

$$\begin{cases} x_8 = x_7 \\ y_8 = y_7 \\ z_8 = z_7 - 3t_4 \end{cases} \tag{6}$$

For this single objective multi parameter optimization problem, this paper adopts a simulated annealing algorithm based on a multi round cycle mechanism to solve it

1.Initialize parameters. By randomly generating initial parameters that are within the feasible range to ensure that the starting point of the parameters is within the feasible domain, and calculating the effective masking time corresponding to the initial parameters, the effective masking time is used as the evaluation index, and the current solution is recorded as the initial optimal solution. Afterwards, further annealing parameters are set. In this question, the initial temperature is, the cooling coefficient is 0.9, and the number of iterations is set to 800.

2.Generate neighborhood solutions. Afterwards, neighborhood new solutions were generated through parameter perturbation, and the objective function of the new solutions was calculated. At the same time, in order to ensure that the difference between the new solution and the current solution was small and avoid jumping to invalid areas, this paper also controlled the amplitude of the perturbation, all of which were small perturbations

3.Determine whether to accept the new solution. After obtaining a new solution, the Metropolis criterion is used to determine whether to accept the new solution. If the new solution is better (i.e., the effective masking time is longer), it is accepted. If the new solution is worse, there is a probability of accepting it. This criterion ensures that when the iteration temperature is high, even if the new solution is poor (effective masking time), there is still a high probability of acceptance, helping to escape from local optima; When the iteration temperature is low, only significantly better solutions are accepted to achieve fine search. The probability calculation formula is shown in formula (7). Finally, compare the current optimal solution with the historical optimal solution. If the current optimal solution is better than the historical optimal solution, update the optimal record[10].

$$P = \exp\left(\frac{f_{new} - f_{now}}{T}\right) \tag{7}$$

4.Autonomous loop solving. After 800 iterations, a single round of simulated annealing resulted in an optimal solution. However, considering that single round simulated annealing may fall into local optima, the code has added a multi round loop mechanism. Firstly, repeat the simulated annealing operation (with a cycle count of 200). At the end of a single round of simulated annealing, record the current optimal effective masking duration. If the difference in effective masking duration between three consecutive rounds is less than 0.1, it is judged to be converged. Then, the loop will be terminated early and the search will be stopped. Finally, the parameter combination with the longest effective masking duration will be selected from the optimal solutions of all rounds as the final output.

5.Update iteration temperature. In the process of using simulated annealing algorithm to solve problems, the temperature of each iteration will decrease with the increase of iteration times. In the early iterations, high annealing temperature (such as the temperature in the first iteration) results in strong global search capability; In the later iterations, a low annealing temperature (such as the temperature in the 100th iteration) is more conducive to focusing on the global optimal solution.

4. Effective shielding time

4.1. Strategy of dropping missiles

The paper used the parameter space traversal method to solve this problem. Firstly, the parameter range is limited by combining constraint conditions. Then, an exhaustive approach is adopted for each drone to traverse possible parameters such as deployment direction, deployment speed, deployment coordinates, and the detonation coordinates of the interference bomb after deployment, in order to construct a potential deployment strategy set. After traversing all combinations, with the goal of maximizing the total effective masking time, find the global optimal solution and visualize the results.

In response to this question, the total effective shielding time calculated in this article is 11.21 seconds. At this time, the effective shielding time formed by each drone after dropping the missile is FY1:4.85 seconds, FY2:4.397 seconds, and FY3:1.97 seconds, respectively. The specific strategy is shown in Table 2.

Table 2. Advertising Strategy

Direction	Speed	Number	pointx(m)	point y(m)	point z(m)	Crack x(m)	Crack y(m)	Crack z(m)	Effective time(s)
183.31	113.2	1	17800	0	1800	17617.2	-10.6	1787.2	3.48
		2	17527.2	-15.8	1800	17277.6	-30.2	1776.1	3.24
		3	17394.2	-23.5	1800	17204.1	-34.5	1786.1	0

Note: X is the standard direction

4.2. Robustness detection

This paper conducted robustness testing and error distribution calculation on the established kinematic model. The established model has good robustness with an average relative error of less than 10% when the noise level is ≤ 10%, and the result error can still be controlled within a certain range. At the same time, the error of problem 1 model is mainly concentrated around 0, which indicates that the deviation of the model is small, that is, the average difference between the simulated masking duration and the theoretical value is not large, and the overall model is not systematically overestimated or underestimated, which further demonstrates the good robustness of the model from the side.

4.3. Analysis of the model

This article has designed clear model solving strategies for different problems. Corresponding kinematic equations were established for the motion processes of interference missiles, cloud clusters, and missiles to quickly determine the effective shielding duration of problem one; By using simulated annealing algorithm, optimal solutions can be obtained quickly with reasonable parameter settings, which improves the overall solving efficiency and achieves the goal of solving the problem.

The method proposed in this article is highly innovative, especially when we combine simulated annealing algorithm with multi loop mechanism to handle single objective optimization problems. This effectively alleviates the limitation of the algorithm being prone to getting stuck in local optima, enhances the global optimization ability, and provides new ideas for similar problems. And the accuracy of the calculation results in this article is good. Through precise analysis of the motion mechanism and time sampling traversal, the accurate effective masking duration of problem one was obtained. Specific advertising strategy parameters and masking duration results were also provided based on the corresponding models, with reasonable data and high credibility.

The limitation of the model constructed in this article is that as the number of drones and jamming missiles increases in the problem scenario, the unknown parameters to be determined within the model will significantly increase, which directly leads to an increase in the overall structural complexity of the model. For example, when using parameter space traversal method to solve problems, a large number of possible unknown parameter combinations need to be computed, which greatly increases the computational load and reduces the efficiency of model solving. In order to address the core issues of high model complexity and large computational complexity, further exploration of more efficient problem-solving algorithms is needed. This paper can compare and analyze intelligent optimization algorithms such as genetic algorithm and particle swarm optimization algorithm with existing parameter space traversal methods to select the single algorithm with the best adaptability or construct an efficient algorithm combination, thereby achieving a reduction in computation time and an improvement in model solving efficiency

5. Conclusion

To enhance the battlefield survivability of personnel and equipment, this paper systematically investigated the deployment strategies of smoke screen interference munitions through kinematic analysis, simulated annealing (SA) algorithms with multi-round cycling mechanisms, and exhaustive search methods. This paper demonstrates that integrating kinematic modeling with advanced optimization algorithms (e.g., SA for high-dimensional problems and exhaustive search for validation) significantly improves smoke screen deployment efficacy. Future work could explore real-time adaptive strategies incorporating dynamic threat updates and hardware-in-the-loop simulations to enhance practical applicability. The methodologies and findings provide a robust foundation for optimizing non-kinetic countermeasures in complex battlefield environments.

References

[1] Xie Y, Sun P, Hou X, et al. Anti-ship missile counter-detection strategies analyzing supported by electronic jamming device[J]. Discover Artificial Intelligence, 2025, 5(1).

[2] Chen X, Wang X, Lu D, et al. Research and analysis on jamming effectiveness of towed decoy[J]. Proceedings of SPIE, 2024, 12981(000):7.

[3] Xiangli W, Su H, Li T, et al. Evaluation Method for Anti-Chaff Jamming Performance of Typical Radio Fuze[J]. Journal of Physics: Conference Series, 2024, 2891(12):122014.

[4] Zhang C, Tao C, Xu Y, et al. Autonomous Defense of Unmanned Aerial Vehicles Against Missile Attacks Using a GRU-Based PPO Algorithm[J]. International Journal of Aeronautical and Space Sciences, 2024(3):25.

[5] Wolfe F. RAND Study Discusses Cellular Networks as an Aid in Locating/Jamming Mobile SAMs[J]. Defense Daily, 2025(Feb.20).

[6] Thurber M. Mitigating the ects of GNSS jamming and spoofing[J]. Aviation International News, 2025, 54(2):7.

[7] Li X, Li S, Gao Z. Assessment of anti-jamming capabilities in infrared-guided missile systems[J]. Physica D: Nonlinear Phenomena, 2025, 481.

[8] Huang L. A Reinforcement Learning Approach to Decision Making of Phased Array Radar Jamming[J]. Membrane Technology, 2024:148-164.

[9] Li Q, Chen W, Chen Z, et al. Jamming effect analysis and reticle parameter identification of infrared spin-scan seeker under dynamic engagement environment[J]. Infrared Physics & Technology, 2024, 136(000):10.

[10] Reim G. How Engineers Developed a GPS-Denied Drone for Less Than $500[J]. Aviation week & space technology, 2024, 186(5):44-44.