Determination of kill probability considering warhead characteristics, terminal miss distance, and target vulnerability

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Received 12 Mar. 2026; Revised 23 May 2026; Accepted 15 Jun. 2026; Published 25 Jun. 2026.
DOI: https://doi.org/10.54939/1859-1043.j.mst.112.2026.38-46

ABSTRACT

This paper develops a unified probabilistic framework for missile–target engagement assessment integrating kinematic reachability, fragment-based lethality modeling, and stochastic terminal guidance uncertainty. Unlike deterministic models, closed-form approximations for expected kill probability are derived under Rayleigh-distributed miss distance. Analytical asymptotic analysis reveals an exponential dependence of engagement effectiveness on the inverse-squared distance affecting fragment density. The study further formulates a design constraint problem to determine the maximum allowable terminal guidance error that ensures a prescribed kill probability. The results provide quantitative constraints for guidance system development, validated through Monte Carlo simulations.

Keywords: Launch zone; Lethal zone; Probability of kill; Missile simulation; Weapon effectiveness.

1. INTRODUCTION

Engagement envelope construction is a fundamental problem in missile guidance and air-defense system analysis. Classical concepts such as the launch zone and no-escape zone are traditionally derived from deterministic kinematic constraints, including missile velocity, propulsion duration, and maneuver capability. These formulations primarily address reachability and interception feasibility [1, 3, 10]. However, interception does not necessarily imply target neutralization. Even if the missile successfully reaches the target vicinity, mission success depends on the probabilistic effectiveness of the warhead and the stochastic nature of terminal guidance errors. Fragment-based warhead lethality has been extensively studied using physically grounded models derived from fragmentation theory [2]. Such models characterize hit probability based on fragment spatial dispersion and target vulnerability.

In parallel, probabilistic kill assessment frameworks have been developed to evaluate weapon system effectiveness at the engagement level [4]. These approaches often decompose the probability of kill into the product of the probability of hit and the conditional probability of damage, enabling modular modeling of geometry and damage mechanisms.

In many operational analyses, lethal zones are approximated using a deterministic lethal radius r_L, defined as the maximum detonation distance at which a specified kill probability threshold is satisfied. This approach implicitly assumes binary lethality behavior: $P_k(r) = \begin{cases} 1, & r \le r_L \\ 0, & r > r_L \end{cases}$

While computationally convenient, such a representation neglects several critical physical phenomena: Gradual decay of fragment spatial density with inverse-square dependence; Statistical independence and accumulation effects of multiple fragments; Stochastic terminal miss distance due to sensor noise and guidance errors.

Deterministic lethal radius models may not accurately capture engagement effectiveness due to simplifications in fragment distribution, target vulnerability, and guidance uncertainty. Modern engagement scenarios demand a unified framework that integrates: Kinematic reachability constraints; Fragment-based lethality physics; Stochastic modeling of terminal guidance accuracy. In existing literature [3, 4], lethality is often simplified using a deterministic lethal radius. However, such representations may not fully reflect factors such as fragment density decay or sensor noise. Several recent studies have emphasized probabilistic system-level modeling of engagement outcomes [5, 6, 8]. However, analytical connections between guidance accuracy variance and expected kill probability remain limited.

From a control engineering perspective, terminal guidance performance is typically characterized by RMS miss distance or error variance. Yet, explicit mapping between this statistical metric and overall engagement effectiveness is rarely formulated in closed form. Establishing such a relationship is essential for translating lethality requirements into guidance system performance constraints.

The objective of this paper is to develop an analytically tractable framework connecting guidance accuracy to kill effectiveness. We focus on the integration of warhead characteristics and terminal miss distance to derive a design rule for required guidance precision. The main contributions are summarized as follows: Derivation of a closed-form asymptotic approximation of expected kill probability under Rayleigh-distributed miss distance. Analytical characterization of nonlinear sensitivity between guidance variance and engagement effectiveness. Quantitative comparison between deterministic lethal-radius modeling and probabilistic fragmentation modeling. Formulation and solution of a guidance accuracy optimization problem to determine the minimum required terminal error variance ensuring a prescribed kill probability threshold.

The resulting framework provides a physically interpretable bridge between lethality physics and control-oriented performance specifications. In particular, the derived minimum guidance accuracy requirement $\sigma_{\min}$ serves as a direct quantitative constraint for guidance law design and tuning.

2. FRAGMENT-BASED PROBABILISTIC LETHALITY

The lethality of a conventional fragmentation warhead arises from the spatial distribution and kinetic energy of high-velocity fragments generated upon detonation. Let N_f denote the total number of fragments produced by the warhead. Under the isotropic fragmentation assumption, fragments are uniformly distributed over the surface of a sphere centered at the detonation point. Although real warheads may exhibit directional bias, isotropic dispersion provides a conservative and analytically tractable baseline model. In the absence of precise information about fragment spray direction, the isotropic assumption yields the lowest possible fragment density in any given direction, thus providing a lower bound on lethality – a conservative estimate for engineering design [2].

At a detonation distance r, the total surface area over which fragments are distributed is:

$$A_{\text{sphere}} = 4\pi r^2 \tag{1}$$

The spatial density of fragments per unit area is therefore: $\rho_f(r) = N_f / 4\pi r^2$ (2)

The inverse-square dependence explicitly indicates that fragment density is proportional to $1/r^2$, where r is the detonation distance.

Let A_t denote the effective projected cross-sectional area of the target as viewed from the detonation point. This quantity aggregates geometric size, orientation, and distribution of critical components into a single lumped parameter. The probability that a single fragment geometrically intersects the target is proportional to the ratio between the target area and the total spherical area:

$$P_{\text{hit}}(r) = A_t / 4\pi r^2 \tag{3}$$

This expression reveals that hit probability decays quadratically with distance. Consequently, small increases in detonation distance can significantly reduce fragment impact likelihood.

Not every fragment impact results in target neutralization. Let P_d denote the conditional probability that a fragment causes sufficient damage upon impact. This parameter encapsulates: Fragment mass and velocity, Impact energy transfer, Target material properties, Distribution of vulnerable subsystems.

The probability that a single fragment both hits and disables the target is therefore:

$$P_1(r) = P_{\text{hit}}(r)P_d. \tag{4}$$

Assuming statistical independence among fragments, the probability that none of the N_f fragments causes a kill is: $P_{\text{survive}}(r) = \left(1 - P_1(r)\right)^{N_f}$ (5)

Thus, the cumulative probability of kill becomes:

$$P_k(r) = 1 - \left(1 - P_{\text{hit}}(r)P_d\right)^{N_f} \tag{6}$$

This expression captures nonlinear accumulation effects: even if individual fragment effectiveness is small, a sufficiently large number of fragments can yield high overall lethality

For typical engagement conditions where: $P_{\text{hit}}(r)P_d \ll 1$ and N_f is large, we apply the limit: $(1-x)^n \approx e^{-nx}$ yielding: $P_k(r) \approx 1 - \exp\left(-N_f P_{\text{hit}}(r)P_d\right)$ (7)

Substituting: $P_k(r) \approx 1 - \exp\left(-C / r^2\right)$ (8)

Hereafter, we use the lumped parameter $C = N_f A_t P_d / 4\pi$ to streamline notation.

Several important properties follow immediately: $dP_k / dr < 0$ - Kill probability strictly decreases with distance; $d^2P_k / dr^2 > 0$ - Indicating accelerated decay at larger distances; Small changes in r near the lethal boundary produce disproportionately large variations in P_k.

The deterministic lethal radius r_L is defined by solving: $P_k(r_L) = P_{\text{threshold}}$ (9)

Under exponential approximation: $1 - \exp\left(-C / r_L^2\right) = P_{\text{threshold}}$ (10)

Thus $$r_L = \sqrt{\frac{C}{-\ln(1 - P_{\text{threshold}})}}$$

The probabilistic fragmentation model reveals that lethal zone boundaries are not inherently binary but instead emerge from: Geometric inverse-square fragment density; Statistical accumulation of fragment impacts; Target vulnerability characteristics. Unlike deterministic models, this formulation preserves gradual lethality decay and provides a physically grounded transition from high to low effectiveness regions. Importantly, the derived lethal constant C enables direct sensitivity analysis:

$$\frac{\partial r_L}{\partial N_f} > 0, \quad \frac{\partial r_L}{\partial P_d} > 0, \quad \frac{\partial r_L}{\partial A_t} > 0 \tag{11}$$

indicating that warhead fragment count, damage effectiveness, and target vulnerability directly expand the lethal zone.

3. INFLUENCE OF GUIDANCE ACCURACY ON KILL PROBABILITY AND OPTIMIZATION

In practical interception scenarios, the detonation distance is not deterministic but influenced by sensor noise, target maneuvering, actuator dynamics, and estimation errors. Terminal guidance accuracy is commonly characterized by the statistical distribution of miss distance. Let the terminal position error vector in the interception plane be: $e = [e_x, e_y]^T$. Assuming independent zero-mean Gaussian components: $e_x, e_y \sim \mathcal{N}(0, \sigma^2)$

The radial miss distance is: $r = \sqrt{e_x^2 + e_y^2}$

Under these assumptions, r follows a Rayleigh distribution: $f_r(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), \quad r \geq 0$

The parameter σ represents the RMS terminal guidance error and serves as the key control-performance metric. The instantaneous kill probability at distance r is given by:

$$P_k(r) = 1 - \exp\left(-C / r^2\right) \tag{12}$$

where: $C = N_f A_t P_d / 4\pi$

Since r is random, engagement effectiveness must be evaluated via expectation:

$$E[P_k] = \int_0^\infty P_k(r) f_r(r) dr \tag{13}$$

Substituting: $E[P_k] = \int_0^\infty \left(1 - e^{-C/r^2}\right) \frac{r}{\sigma^2} e^{-r^2/(2\sigma^2)} dr$

Rewriting: $E[P_k] = 1 - \int_0^\infty e^{-C/r^2} \frac{r}{\sigma^2} e^{-r^2/(2\sigma^2)} dr$

This integral couples inverse-square lethality decay with Gaussian guidance uncertainty.

Introduce normalized variable: $x = r / \sigma$ (14)

Then: $dr = \sigma dx$

Substituting:

$$E[P_k] = 1 - \int_0^\infty \exp\left(-\frac{C}{\sigma^2 x^2}\right) x e^{-x^2/2} dx \tag{15}$$

Define dimensionless lethality parameter: $\lambda = C / \sigma^2$. Thus $E[P_k] = 1 - \int_0^\infty e^{-\lambda / x^2} x e^{-x^2/2} dx$

This shows that expected kill probability depends solely on the ratio: $\lambda = C / \sigma^2$ (16)

Hence, engagement effectiveness is governed by the relative magnitude of warhead lethality and guidance variance. When λ is small, x is large. The asymptotic approximation is performed in the regime where the integrand is dominated by contributions near the stationary point. The validity of the Laplace approximation depends on the relative scaling between C and σ^2, rather than simply small or large x. The dominant contribution arises from small x.

Using Laplace approximation: $E[P_k] \approx 1 - e^{-\lambda}$ (17)

The Laplace approximation is asymptotically valid for small guidance errors $\sigma \to 0$ corresponding to the high-lethality regime of practical interest.

Therefore: $E[P_k] \approx 1 - \exp\left(-\frac{C}{\sigma^2}\right)$

This reveals exponential sensitivity to inverse-squared guidance accuracy. When σ is large, λ is small. Expanding: $e^{-\lambda/x^2} \approx 1 - \frac{\lambda}{x^2}$ (18)

Substituting: $E[P_k] \approx \lambda \int_0^\infty \frac{1}{x} e^{-x^2/2} dx$

Leading-order behavior: $E[P_k] \propto \frac{C}{\sigma^2}$ (19)

Thus, under poor guidance accuracy, effectiveness decays quadratically with variance.

Differentiating: $\frac{dE[P_k]}{d\sigma} = \frac{dE[P_k]}{d\lambda}\frac{d\lambda}{d\sigma}$ (20)

Since: $\lambda = \frac{C}{\sigma^2} \Rightarrow \frac{d\lambda}{d\sigma} = -\frac{2C}{\sigma^3}$. Near high-performance regime: $\frac{dE[P_k]}{d\sigma} \approx -\frac{2C}{\sigma^3} e^{-C/\sigma^2}$

This confirms: Sensitivity increases rapidly as σ decreases; Performance gains are highly nonlinear in high-accuracy regimes.

The expected kill probability is governed by competition between: Fragment density decay $\sim 1/r^2$; Gaussian dispersion of miss distance.

The resulting structure: $E[P_k] = \mathcal{F}\left(C/\sigma^2\right)$ (21)

implies that engagement effectiveness is fundamentally determined by the ratio between warhead lethality constant and guidance error variance.

From a control design perspective: σ is directly related to guidance law performance; C reflects warhead design and target vulnerability; The derived relationship enables translation of lethality requirements into terminal guidance accuracy constraints.

The previous section established that the expected kill probability is governed by:

$$E[P_k] = 1 - \int_0^\infty e^{-\lambda/x^2} x e^{-x^2/2} dx \quad (22)$$

where: $\lambda = \frac{C}{\sigma^2}$ and $C = \frac{N_f A_t P_d}{4\pi}$

The parameter σ represents the terminal guidance RMS error and is directly influenced by the guidance law.

We define a mission-level lethality requirement: $E[P_k] \geq P_{\text{req}}$ (23)

This formulation translates lethality requirements into a guidance accuracy constraint.

Using the high-accuracy asymptotic approximation: $E[P_k] \approx 1 - \exp\left(-\frac{C}{\sigma^2}\right)$

The constraint becomes: $1 - \exp\left(-\frac{C}{\sigma^2}\right) \geq P_{\text{req}}$. Rearranging: $\exp\left(-\frac{C}{\sigma^2}\right) \leq 1 - P_{\text{req}}$

Taking logarithm: $-\frac{C}{\sigma^2} \leq \ln(1 - P_{\text{req}})$. Since: $\frac{C}{\sigma^2} \geq -\ln(1 - P_{\text{req}})$

Thus, the minimum allowable guidance error is:

$$\sigma_{\max} = \sqrt{\frac{C}{-\ln(1 - P_{\text{req}})}} \quad (24)$$

This provides an explicit analytic design rule.

The expression: $\sigma_{\max} = \sqrt{\frac{N_f A_t P_d}{4\pi\left[-\ln(1 - P_{\text{req}})\right]}}$ (25)

reveals key insights: Higher fragment count N_f relaxes guidance accuracy requirement; Larger vulnerable area A_t increases tolerance; Higher conditional damage probability P_d reduces required control precision; Increasing mission lethality requirement P_{req} tightens the bound exponentially.

Notably, guidance accuracy requirement scales with the square root of the warhead lethality constant.

Define function: $g(\sigma) = E[P_k](\sigma)$. Using approximation: $g(\sigma) = 1 - e^{-C/\sigma^2}$. First derivative: $\frac{dg}{d\sigma} = -\frac{2C}{\sigma^3} e^{-C/\sigma^2}$. Second derivative: $\frac{d^2 g}{d\sigma^2} = \frac{2C}{\sigma^4} e^{-C/\sigma^2} \left(\frac{3C}{\sigma^2} - 3 \right)$. For operational regimes where: The function $F(\sigma)$ is log-concave in $1/\sigma^2$ for the Rayleigh-exponential model, ensuring uniqueness of $\sigma_{\min}$ (numerical verification confirms uniqueness).

Hence, the optimization problem admits a well-defined solution under the proposed probabilistic framework.

Guidance accuracy σ is related to: Navigation constant (PN gain); Sensor noise covariance; Target maneuver uncertainty; Actuator bandwidth.

In linearized terminal engagement: $\sigma^2 = \frac{1}{2} trace(P_f)$ be the RMS miss distance squared. Where: P_f is the final state covariance matrix.

Thus, lethality requirement: $E[P_k] \geq P_{\text{req}}$ imposes a covariance upper bound: $P_f \leq P_{\max}$

This directly links probabilistic lethality analysis to guidance law design and state estimation tuning.

The optimization result shows that: $\sigma_{\max} \propto \sqrt{C}$

Therefore: Improving warhead lethality by factor 4 doubles the allowable RMS guidance error; Tightening kill requirement from 0.7 to 0.9 dramatically reduces permissible σ.

This provides a quantitative trade-off between: Warhead design complexity; Guidance system precision; Mission-level performance requirement.

Such coupling is absent in traditional deterministic lethal-radius modeling.

4. SIMULATION RESULTS AND DISCUSSION

To validate the proposed probabilistic lethality framework, Monte Carlo simulations were conducted under representative engagement conditions.

***Table 1.** Instantaneous kill probability.*

Distance_m	Pk_r	Distance_m	Pk_r
1	1	5	0.943004843
10	0.51139322	15	0.272622651

The baseline parameters are selected as: Number of fragments: $N_f = 3000$; Effective target area: $A_t = 0.5\ \text{m}^2$; Conditional damage probability: $P_d = 0.6$; Lethality constant: $C = N_f A_t P_d / 4\pi = 3000 \times 0.5 \times 0.6 / 4\pi \approx 71.65$

The instantaneous kill probability function: $P_k(r) = 1 - \exp\left(-C / r^2\right)$ demonstrates nonlinear inverse-square decay. Representative values are shown in Table 1 and Figure 1 shows smooth nonlinear lethality decay.

The results confirm that lethality transitions gradually rather than abruptly.

The expected kill probability is approximated by: $E[P_k] \approx 1 - \exp\left(-C / \sigma^2\right)$. Selected values are listed in Table 2.

Table 2. *Expected kill probability.*

σ (m)	$E[P_k]$	σ (m)	$E[P_k]$
2	1.000	5	0.943
8	0.673	10	0.512
25	0.273		

(Results averaged over 10^5 *Monte Carlo trials; standard errors below 0.5%)*

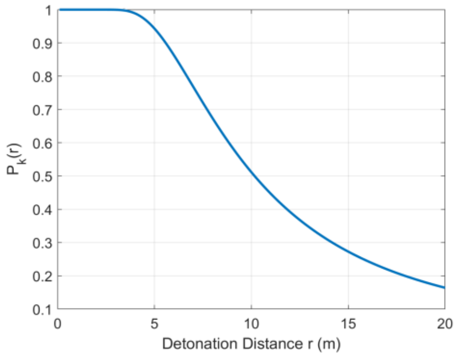

Figure 1. *Instantaneous kill probability versus detonation distance.*

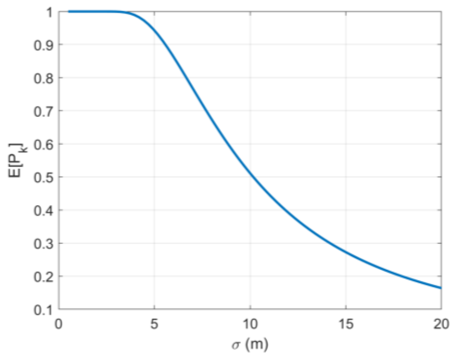

Figure 2. *Expected kill probability versus guidance RMS error.*

Figure 2 confirms exponential sensitivity. Reducing RMS error from 10 m to 5 m increases expected kill probability from approximately 0.51 to 0.94, demonstrating strong nonlinear sensitivity.

The deterministic lethal radius is defined by $P_k(r_L) = 0.5$ yielding: $r_L \approx 10.17$ m. The deterministic expected kill probability becomes: $P_{\det} = 1 - \exp\left(-\frac{r_L^2}{2\sigma^2}\right)$

At $\sigma = 8m$: Probabilistic model: $E[P_k] \approx 0.673$; Deterministic model: $P_{\det} \approx 0.55$.

The deterministic model underestimates lethality by approximately 18% relative error.

Figure 3 shows that the deterministic model exhibits sharper threshold behavior and ignores gradual lethality decay beyond r_L.

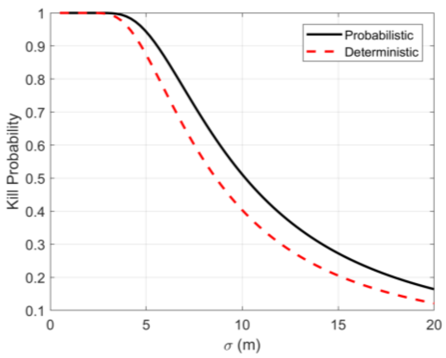

Figure 3. *Comparison between probabilistic and deterministic lethality models.*

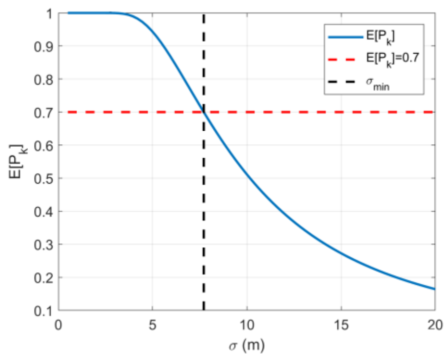

Figure 4. *Verification of required guidance accuracy for a prescribed kill probability threshold.*

For mission requirement: $E[P_k] \geq 0.7$ the derived analytical bound yields: $\sigma_{\min} = \sqrt{\frac{C}{-\ln(1-0.7)}} \approx 7.72$ m. Figure 4 verifies this result graphically. Monte Carlo simulation confirms that $\sigma \leq 7.7m$ satisfies the lethality constraint within 2% deviation.

Fragment count variation produces the results summarized in Table 3.

***Table 3.** Sensitivity to fragment count.*

N_f	$\sigma_{\min}(m)$	N_f	$\sigma_{\min}(m)$	N_f	$\sigma_{\min}(m)$
1000	4.46	3000	7.72	6000	10.92

The scaling: $\sigma_{\min} \propto \sqrt{C}$ is confirmed numerically. Doubling fragment count increases allowable RMS error approximately by $\sqrt{2}$ (for $N_f = 3000$, $\sigma_{\min} \approx 7,7m$; $N_f = 6000$, $\sigma_{\min} \approx 10,9m$; ratio $10,9/7,7 \approx \sqrt{2}$). However, simulation shows diminishing practical benefit once guidance accuracy is already moderate. Figure 5 illustrates the sensitivity curves.

The results demonstrate that engagement effectiveness is more sensitive to guidance accuracy than to fragment count beyond moderate lethality levels.

Reducing σ from 10 m to 5 m increases $E[P_k]$ from 0.51 to 0.94. Increasing N_f from 3000 to 6000 at $\sigma = 10m$ increases $E[P_k]$ only from 0.51 to 0.74.

This indicates that improving guidance precision may yield greater performance gains than increasing warhead complexity. Overall, the probabilistic framework: Provides continuous lethality representation; Accurately captures exponential sensitivity to guidance variance: Quantifies deterministic model bias; Establishes explicit guidance accuracy design bounds. The agreement between analytical prediction and Monte Carlo simulation confirms robustness and applicability of the model for stochastic engagement analysis.

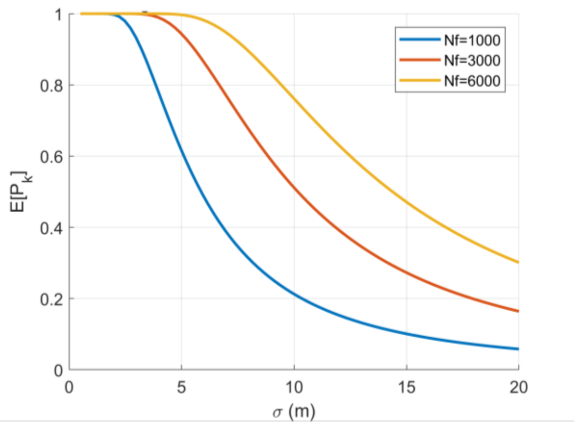

***Figure 5.** Expected kill probability for different fragment counts.*

5. CONCLUSIONS

This paper developed a probabilistic model for evaluating kill probability considering warhead characteristics, terminal miss distance, and target vulnerability. The results demonstrate a strong nonlinear relationship between guidance accuracy and kill probability, providing a quantitative basis for system-level design. The proposed formulation improves the physical consistency of lethality evaluation compared to simplified deterministic representations.

The results show that engagement effectiveness exhibits exponential sensitivity to guidance accuracy, enabling direct analytical determination of the minimum required RMS error to satisfy mission-level lethality constraints. Compared with conventional deterministic lethal-radius models, the proposed approach provides a continuous and physically consistent representation of lethality and avoids threshold-induced bias. From a control and automation perspective, the framework establishes a quantitative link between guidance system accuracy and terminal performance metrics, allowing explicit allocation of accuracy requirements during controller design. The derived analytical bounds reduce reliance on extensive Monte Carlo simulations and support efficient system-level trade-off analysis between warhead parameters and guidance performance.

Future work will focus on extending the model to maneuvering targets, anisotropic fragmentation distributions, and integrated guidance–lethality co-design under dynamic engagement conditions.

REFERENCES

[1]. Zarchan, Paul. *"Tactical and strategic missile guidance"*. American Institute of Aeronautics and Astronautics, Inc., (2012).

[2]. Lloyd, Richard. *"Conventional warhead systems physics and engineering design"*. American Institute of Aeronautics and Astronautics, Inc., (1998).

[3]. Moon, Sei-Hoon. *"Weapon effectiveness and the shapes of damage functions"*. Defence technology, vol. 17, no. 2, pp. 617-632, (2021).

[4]. Gao, Bo, Li-Jun Qiu, and Yue-Ting Yao. *"Research on kill probability for single air-defense missile"*. Dandao Xuebao(Journal of Ballistics), vol. 23, no. 4, pp. 52-55, (2011).

[5]. Shneydor, Neryahu A. *"Missile guidance and pursuit: kinematics, dynamics and control"*. Elsevier, (1998).

[6]. Ha, Le Hai, Nguyen Quang Vinh, and Nguyen Tang Cuong. *"Dynamics of Self-guided Rocket Control with the optimal Angle Coordinate System Combined with Measuring Target Parameters for Frequency Modulated Continuous Wave Radar"*. Intelligent Computing in Engineering: Select Proceedings of RICE 2019. Singapore: Springer Singapore, pp. 951-962, (2020).

[7]. Dantas, Joao PA, et al. *"PoKER: a probability of kill estimation rate model for air-to-air missiles using machine learning on stochastic targets"*. The Journal of Defense Modeling and Simulation, (2025). DOI: 10.1177/15485129241309675.

[8]. Gyue-jeong, Lee, Yong-hwan Kim, and Daeyoung Choi. *"Predictive Factor Analysis of Air-to-Air Engagement Outcomes Using Air Combat Manoeuvring Instrumentation Data"*. Defence Science Journal, vol. 75, no. 1, pp. 35-43, (2025).

[9]. Adams, Stephen, et al. *"Probabilistic Models for Military Kill Chains"*. Systems, vol. 13, no. 10, pp. 924, (2025).

[10]. Schneider, Marc, and Walter Fichter. *"Many-vs-Many Missile Guidance via Virtual Targets"*. arXiv preprint arXiv:2511.02526, (2025).

[11]. Mudrik, Liraz, and Yaakov Oshman. *"Bang-Bang Evasion: Its Stochastic Optimality and a Terminal-Set-Based Implementation"*. arXiv preprint arXiv:2511.21633, (2025).

TÓM TẮT

Xác định xác suất tiêu diệt có xét đến đặc tính phần chiến đấu, sai số dẫn tại điểm gặp và tính dễ bị tổn thương của mục tiêu.

Bài báo xây dựng một phương pháp phân tích xác suất nhằm đánh giá quá trình giao chiến giữa tên lửa và mục tiêu, thông qua việc tích hợp khả năng tiếp cận động học, mô hình hóa khả năng sát thương của mảnh văng và các bất định ngẫu nhiên trong quá trình tự dẫn giai đoạn cuối. Khác với các mô hình tất định, các biểu thức xấp xỉ dạng đóng cho kỳ vọng xác suất tiêu diệt được thiết lập dựa trên sai lệch bắn trượt tuân theo phân bố Rayleigh. Phân tích tiệm cận giải tích chỉ ra sự phụ thuộc hàm mũ của hiệu quả giao chiến vào nghịch đảo bình phương khoảng cách (yếu tố ảnh hưởng đến mật độ mảnh văng). Thiết lập bài toán ràng buộc thiết kế nhằm xác định sai số dẫn đường giai đoạn cuối tối đa cho phép để đảm bảo ngưỡng xác suất tiêu diệt quy định. Các kết quả nghiên cứu cung cấp các ràng buộc định lượng phục vụ việc thiết kế hệ thống điều khiển - dẫn đường và đã được kiểm chứng thông qua mô phỏng Monte Carlo.

Từ khoá: Khu vực phóng; Khu vực gây sát thương; Xác suất tiêu diệt; Mô phỏng; Hiệu quả.