IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 2 August 2023, accepted 26 August 2023, date of publication 30 August 2023, date of current version 6 September 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3310214

RESEARCH ARTICLE

A Virtual Reality Approach to the Assessment of Damage Effectiveness of Naval Artillery Ammunition Against Unmanned Surface Vessels

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This work was supported in part by the 2023 Central Guiding Fund for Local Science and Technology Development under Grant 2023JH6/100100066, in part by the Liaoning Province Basic Research Projects of Higher Education Institutions under Grant LJKZ0239, and in part by the Program for Liaoning Innovative Talents in University under Grant LG202107.

ABSTRACT Conventional evaluations of naval artillery's destructive prowess are dependent on resource-intensive sea trials, which are neither economically viable nor advantageous for the cultivation of combat intelligence. To circumvent these limitations, we propose a method rooted in virtual reality for assessing the destructive efficacy of naval artillery ammunition against unmanned maritime targets. Leveraging the Unity3D engine, we construct a high-fidelity virtual testing environment and design corresponding testing tasks. The offensive strategy is devised considering the naval artillery's damage radius and range, incorporating factors such as the warhead's velocity, and determining its launch angle and direction. Following this, the projectile's trajectory is computed employing the point mass motion equation, facilitating the simulation of the projectile's entire life cycle trajectory. A Monte Carlo based model has been developed for assessing the damage effectiveness of naval artillery ammunition against unmanned boats. This model enables quantitative calculation of ammunition usage under varied damage probabilities, addressing issues related to the complexity of the testing process, the limited number of tests, and the challenges in computing damage probabilities for target impacts of naval artillery ammunition. The findings corroborate the precision and stability of the virtual reality based assessment method for naval artillery ammunition damage effectiveness against unmanned surface vessels in combat simulations. This verification holds substantial importance for enhancing the computation accuracy of damage effectiveness associated with naval artillery ammunition.

INDEX TERMS Damage effectiveness, naval artillery, virtual reality, unmanned surface vessel.

I. INTRODUCTION

Damage effectiveness assessment is integral to ammunitions design, combat strategy formulation, and attack plan development [1], [2], [3], [4]. Accurate and quantitative evaluation of missile effectiveness against enemy battle groups, based on the ammunition's destructive capacity, is essential [5], [6]. The efficacy of naval operations is increasingly reliant on effective strike damage against unmanned platforms like unmanned surface vessels (USVs) [7], [8], [9]. Naval artillery, fundamental to naval weapon systems, fulfill diverse mission objectives such as air and missile defense, anti-surface warfare, the escort and recovery of islands and reefs, and the resolution of minor maritime conflicts. As a result, research investment has dramatically increased to evaluate the destructive impact of naval artillery ammunition on

The associate editor coordinating the review of this manuscript and approving it for publication was Tai-Hoon Kim.

unmanned boats worldwide [10]. Various countries, including Norway, Finland, and the U.K., have set up numerous maritime test sites. Likewise, China has built comprehensive maritime testing facilities in Weihai (Shandong), Wanshan (Guangdong), and Zhoushan (Zhejiang) [11], [12]. However, progressing research has met with significant obstacles, including intricate testing scenarios and substantial costs. Authentic damage assessment experiments require live naval artillery against USVs, resulting in countless tests that inflict near-irreversible damage on USVs. Implementing all live ship tests would require massive time and financial investments, thus existing maritime test ranges are inadequate to meet the high-quality exercise mission testing demands. As a result, researchers are turning their attention to risk-free, cost-effective virtual testing methods.

In this study, we use the Unity3D engine to construct a virtual environment that mirrors actual scenarios of naval artillery strike tests against unmanned boat targets. The virtual environment includes 3D models of various components, such as the destroyer, unmanned boat, naval artillery, shells, and other objects. It also replicates weather conditions like the sky, seawater, rain, fog, and sea wind. The simulation replicates the real naval artillery's speed and firing rate, and it calculates the aiming point based on the position of the unmanned boat target and the pre-determined attack plan. Subsequently, the naval artillery's firing angle and direction are adjusted, the shell's trajectory is calculated, and the Monte Carlo method is utilized to estimate the likelihood of damage to the ammunition's combat component upon impact. ''Single shot damage probability'' and ''required ammunition quantity to achieve a certain damage probability'' are used as primary quantitative indicators to evaluate the damage effectiveness of the warhead. This study uses these two metrics to perform multiple experiments in simulated scenarios, greatly saving manpower and resources compared to conducting all tests on a real ship. We propose a new testing approach for assessing new equipment and executing tactical exercises at sea.

The primary contributions of this study can be summarized as follows:

1) A novel method for damage effectiveness assessment is introduced, offering a more efficient alternative to traditional real ship testing. This approach aligns with the advancement of naval combat intelligence, significantly reducing the cost of pre-testing new naval weapons. It also facilitates the rehearsal of naval combat scenarios and promotes the enhancement of combat effectiveness on the naval battlefield.
2) The Unity3D engine was employed to create realistic virtual test environments, which include simulations of the sky and seawater. This includes the creation of 3D models for objects like destroyer, USVs naval artillery, and shells, and the simulation of typical maritime meteorological conditions, such as sea breeze and sea fog.
3) The comprehensive process of naval artillery ammunition striking a USV was simulated, which included the calculation of the naval artillery's speed, velocity, angle, and firing direction. The study also involved the simulation of the projectile's random trajectory and rendezvous process, the statistical assessment of damage probability using the Monte Carlo method, and the deployment of a virtual testing method to evaluate the damage effectiveness of naval artillery ammunition against USV targets.

The remaining sections of the thesis are structured as follows: Section II offers a brief review of related work, with a focus on the application of virtual reality (VR) methods to ship simulations and conventional damage effectiveness assessment techniques. Section III presents a detailed description of the virtual test scenario construction. Section IV details the experiments conducted and the subsequent analysis of the results. Finally, Section V summarizes the main conclusions drawn from the study and the prospective future work.

II. RELATED WORK

Future maritime warfare will be characterized by joint, three-dimensional, distributed, and comprehensive mobile military operations [13]. This form of warfare utilizes the sea for maneuvers, originates from the sea, and projects force and firepower onto both sea and land islands. This makes it a high-risk and complex operation, both strategically and tactically. Researchers explored various methods to assess the effectiveness of weapons in such complex scenarios. Sei-Hoon Moon reviewed methods for assessing the effectiveness of fragmentation weapons against specific and area targets, emphasizing the importance of using the Carleton damage function with the appropriate shape factor [14]. It informs the development of precision-guided ammunitions to minimize collateral damage. H. Liu proposed a method to calculate the damage impact of ammunitions on targets based on Multinomial Naive Bayes (MNB) [15]. The approach addresses the challenges of complex high-tech ammunition testing processes, limited test instances, and difficult damage probability calculations. Li developed a model for calculating the position of damage elements impacting the damage target by utilizing the relative spatial coordinates of the combat fragment and the damage target [16]. In 2022, Li introduced a novel approach to studying the calculation model of target damage effectiveness assessment under the uncertainty of combat fragmentation information, employing a multi-layer combat fragmentation distribution mechanism [17]. Wu et al. proposed a new model based on an adaptive fuzzy neural network system (ANFIS) to assess the damage effectiveness of artillery fire on clustered targets [18]. Shi et al. suggested a method for evaluating the effectiveness of anti-ship missile combat components based on an integrated blast calculation approach with multiple damage effects [19]. While experts and scholars modeled and analyzed typical target destruction effectiveness evaluation methods, experimental results remain at the theoretical reasoning stage and still necessitate a substantial number of real ship tests. Such approach is not only inefficient and costly but also struggles to adapt to complex climate and combat environment changes and the requirements of intelligent combat development. Therefore, this study introduces a zero-risk, cost-effective virtual testing technology.

Virtual testing technology is a technique for evaluating the performance and functionality of test models according to predefined criteria within a simulated environment. Zhu et al. proposed a collaborative testing and evaluation method for unmanned vessel formations based on VR fusion [20]. Han et al. introduced a novel approach for parallel testing and evaluation of USV autonomous navigation algorithms, building a parallel test system that accommodates a variety of scenarios and tasks [21]. This parallel system effectively simulates real-world environments for USVs with various autonomous navigation tasks and algorithms, thereby facilitating efficient evaluation methods. Lin developed a virtual test platform that employs VR technology to test and evaluate the diving performance of underwater vehicles in real-time [22]. Ong et al. utilized a VR based interface that enables testers to interact with a virtual prototype for performance evaluation [23]. Hu and Qian implemented virtual shipbuilding based on modern shipbuilding models and advanced manufacturing technologies [24]. Yang and Fan proposed the application of simulator technology and virtual testing technology for ship performance testing in China for the first time, establishing a general framework for a virtual testing system for ship navigational performance [25]. Fan et al. designed a USV-assisted navigation posture display system based on virtual-real fusion, using VR technology to construct a virtual navigation environment for USVs and enhancing the visualization of the display system [26]. Virtual testing offers a low-cost, high-efficiency, and risk-free evaluation of the destructive effectiveness of naval artillery ammunition. The resulting assessments are more credible and better aligned with the development of naval combat intelligence than those derived from traditional verification environments.

III. CONSTRUCTION OF THE VIRTUAL TEST SCENARIO FOR DAMAGE EFFECTIVENESS ASSESSMENT

In assessing the destructive impact of naval artillery ammunition on unmanned boat targets using virtual testing, the primary aim is to leverage virtual simulation technology to devise realistic test scenarios grounded in true navigational and combat data. This process includes the creation of simulated weather conditions, marine environments, and both friendly and hostile navigation scenarios, thereby accurately depicting real combat situations. Fig. 1 delineates the basic framework of the experiment.

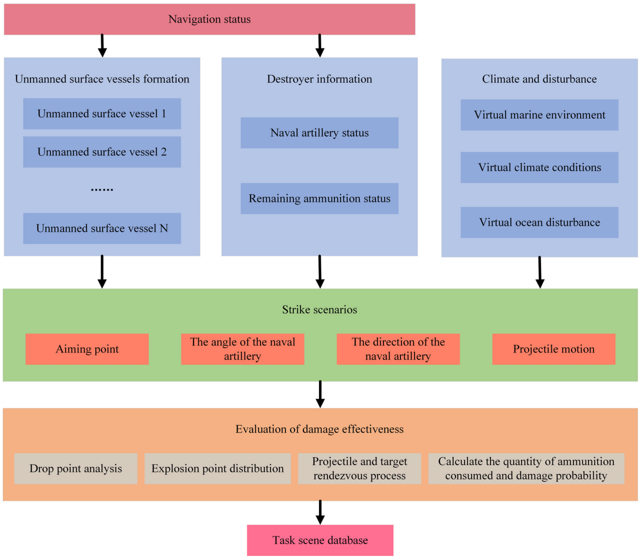


FIGURE 1. Virtual reality based framework for assessing damage effectiveness.

This study employs Unity3D to develop a system to assess the damage effectiveness of naval artillery against USVs. With multi-platform support, Unity3D facilitates straightforward cross-platform development and deployment [27]. Moreover, Unity3D's robust physics engine and effects system enable the simulation of realistic physics and environmental effects, thereby augmenting the realism of virtual test scenarios and providing a more precise grasp of the test process for users [28]. Unity is used to construct a virtual marine environment, formulate the destroyer and USV formations, model the path of projectile movement, create a sea fog visibility weather model incorporating sea breeze and other disturbances, and simulate diverse weather conditions for damage effectiveness testing [29], [30]. Test scenarios of differing complexities are designed, taking into account factors such as weather, sea conditions, visibility, terrain, and USV formations, thereby satisfying test requirements.

The testing tasks for evaluating the damage effectiveness of naval artillery ammunition encompasses USV formation, environmental awareness, pre-aiming point computation, analysis of projectile motion trajectory, blast point distribution patterns, simulation of projectile and target interception process, and calculation of damage effectiveness. The virtual testing scenario incorporates various elements to closely mimic real-world combat situations. The components of this virtual scenario are illustrated in 2. Considering that USV formations may adopt various formation patterns depending on factors such as load carried, mission objectives, and random maneuvers, it is crucial to consider the evaluation needs of various combat missions during testing. Therefore, we propose three typical forms of USV combat formations, as presented in Table 1, with the layout of each formation type illustrated in Fig. 3.

Key technologies for damage effectiveness assessment include ship information aggregation, environmental

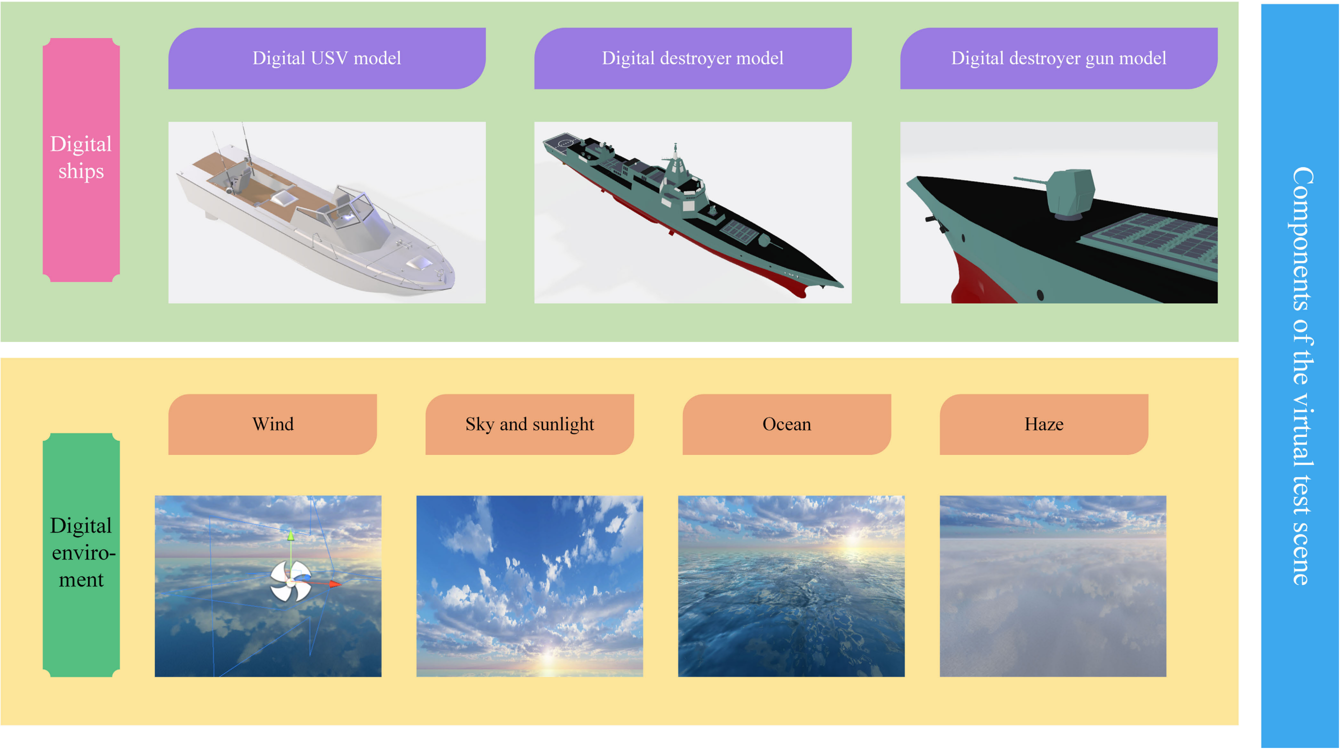


FIGURE 2. Elements of the virtual test environment.

TABLE 1. Three representative types and designations of USV formations.

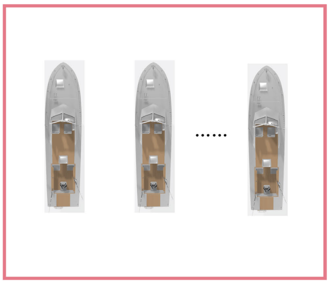
Types	Designations
I	Transoceanic maneuvering formation
II	Assault combat formation
III	Random combat formation

awareness, decision planning, projectile motion process simulation, and damage probability statistics [31]. The implementation hierarchy of the virtual damage effectiveness test is depicted in Fig. 4. Fig. 4 demonstrates that the perception layer forms the backbone of the entire virtual test system, responsible for sensing the environment, information collection, and fusing environmental information. The decision layer ingests present environmental data, static or dynamic obstacle details, and the status of each unmanned vessel relayed from the perception layer. Based on this information, it assesses the current scenario, formulates an attack strategy, computes the projectile's pre-target point, and enforces a control strategy for the naval artillery, substituting human decision-making. The execution layer is responsible for testing the system's precision in executing planned tasks and simulating projectile flight behavior. The damage effectiveness virtual test scenario is a complex system, comprising three interactive components: environmental awareness, planning and decision-making, and control and execution. To address the limitations of single test scenarios, low efficiency, and high costs in maritime test sites, the virtual system requires comprehensive testing capabilities for environmental awareness, planning and decision-making, and control and execution. VR is integrated with representative and typical virtual scenarios as the primary component, supplemented by rare and extreme scenarios, to build a virtual testing environment.

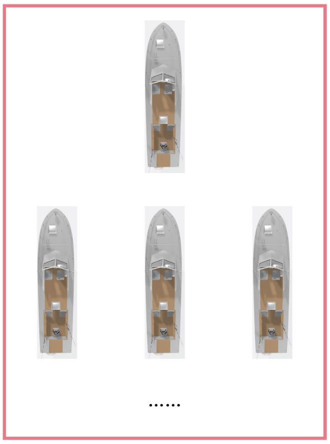
IV. ASSESSMENT OF THE DESTRUCTIVE EFFECTIVENESS OF NAVAL ARTILLERY AMMUNITION AGAINST USV TARGETS

A. DAMAGE EFFECTIVENESS ASSESSMENT MODEL

This study focuses on a large-caliber, semi-armor-piercing projectile intended for destroyer deployment. The warhead primarily consists of explosives and metal shells, serving multiple functions such as anti-personnel and damaging equipment within a compartment [32]. Upon striking a ship's target, semi-armor-piercing shells explode within the compartment, generating fragmentation and shockwaves. The distribution law of the blast and shockwave overpressure within the compartment is determined based on theoretical formulas [33], [34]. Firstly, the horizontal plane containing the personnel and equipment of a representative compartment is discretized, followed by subdividing the cell grid and establishing the coordinates of each cell grid. Considering the coordinates of the blast point, the fragmentation and blast load distribution pattern is resolved, generating the peak overpressure and effective fragmentation density for each cell grid. Each compartment's damage probability is calculated by



(b) Assault combat formation



(a) Transoceanic maneuvering formation (c) Random combat formation

FIGURE 3. **Typical USV formation.**

weighting the damage probabilities of the cell grids. In the evaluation of damage effectiveness, “single shot damage probability” and “required ammunition quantity to achieve a certain damage probability” serve as the primary quantitative measures of a combatant’s damage effectiveness [35]. We propose a mathematical model to calculate the damage effectiveness of naval artillery ammunitions striking a USV, applicable to assessing ship target damage effectiveness.

The geometric center of the Unmanned Surface Vehicle (USV) cluster target serves as the origin (O), and the USV cluster’s movement direction forms the OX_t axis. The OY_t axis is set as the axis orthogonal to the OX_t axis, and the OZ_t axis is orthogonal to the $O - X_tY_t$ plane, as determined by the right-hand rule. The establishment of the target coordinate system, as illustrated in Fig. 5, is critical to the formulation of the attack plan. Given a specific USV cluster target formation, the coordinates of the jth target within the coordinate system can be denoted as (x_{oj}, y_{oj}). Subsequently, the coordinates of this target in the global coordinate system (x_{gj}, y_{gj}) can be expressed according to (1).

$$\begin{bmatrix} x_{gj} \\ y_{gj} \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} x_{oj} \\ y_{oj} \end{bmatrix} \tag{1}$$

where β is the angle between the OX_t axis in the target coordinate system and the OX_g axis in the world coordinate system. The equation of motion for the center of mass of the naval projectile is represented by (2).

$$\begin{cases} \dfrac{dv_x}{dt} = \dfrac{R_x}{m_0} \\ \dfrac{dv_y}{dt} = \dfrac{R_y}{m_0 - g} \\ \dfrac{dv_z}{dt} = \dfrac{R_z}{m_0} \\ \dfrac{dx}{dt} = v_x \\ \dfrac{dy}{dt} = v_y \\ \dfrac{dz}{dt} = v_z \end{cases} \tag{2}$$

where t denotes time, m_0 refers to the mass of the projectile, and v_x, v_y, and v_z correspond to the projections of the center of mass velocity of the projectile in the world coordinate system. Moreover, x, y, and z correspond to the coordinates of the projectile’s center of mass in the world coordinate system. The gravitational acceleration, g, is expressed by the (3).

$$g = g_0 \left(1 + \frac{y}{R_0}\right)^{-2} \tag{3}$$

where g_0 refers to the standard Earth value of gravity ($9.8m/s^2$) and R_0 indicates the effective radius of the Earth ($6358.922km$). The drag force projections, R_x, R_y, and R_z, acting on the projectile in the world coordinate system, are illustrated in (4).

$$\begin{pmatrix} R_x \\ R_y \\ R_z \end{pmatrix} = -\frac{1}{2}\rho S C_x (Ma)\, v_r \begin{pmatrix} v_x - w_x \\ v_y \; v_z - w_z \end{pmatrix} \tag{4}$$

where ρ represents air density, S denotes the maximum cross-sectional area of the projectile, $C_x (Ma)$ signifies the drag coefficient, and v_r refers to the relative velocity. The relative velocity is defined as the vector difference between the absolute velocity ($\vec{v}$) and the wind speed ($\vec{w}$), which can be computed using (5).

$$v_r = \sqrt{(v_x - w_x)^2 + {v_y}^2 + (v_z - w_z)^2} \tag{5}$$

where w_x and w_z represent the decomposition of wind speed ($\vec{w}$) into vertical and horizontal components within the world coordinate system. These components can be calculated using (6).

$$\begin{cases} w_x = -w\cos(\tau_w - \alpha_N) \\ w_z = -w\sin(\tau_w - \alpha_N) \end{cases} \tag{6}$$

where w denotes the magnitude of wind speed, τ_w represents the angle between wind direction and due north, and α_N signifies the angle between the projectile’s direction and due north.

The Monte Carlo method is employed to compute the destruction probability of the warhead. To achieve this, it necessitates generating a pair of random numbers that comply with the hit accuracy and fuze activation law. These random numbers should uniformly distribute within the range

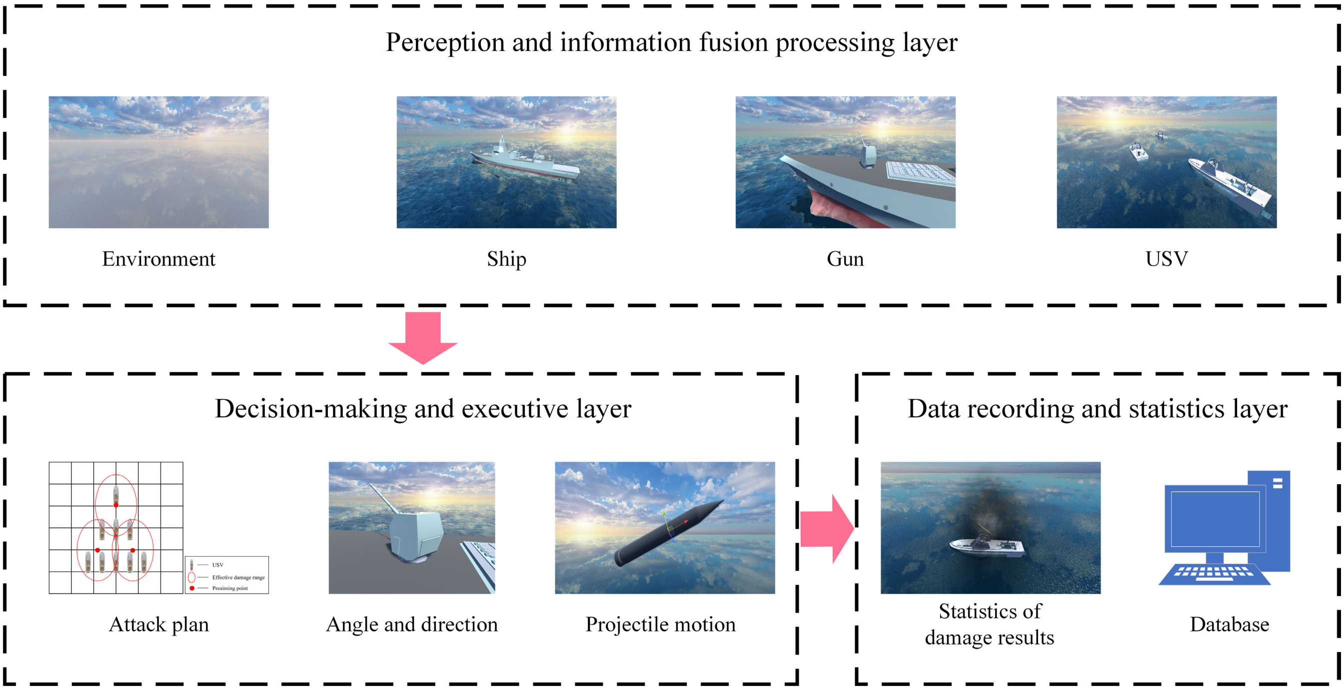


FIGURE 4. Hierarchy of virtual damage effectiveness test.

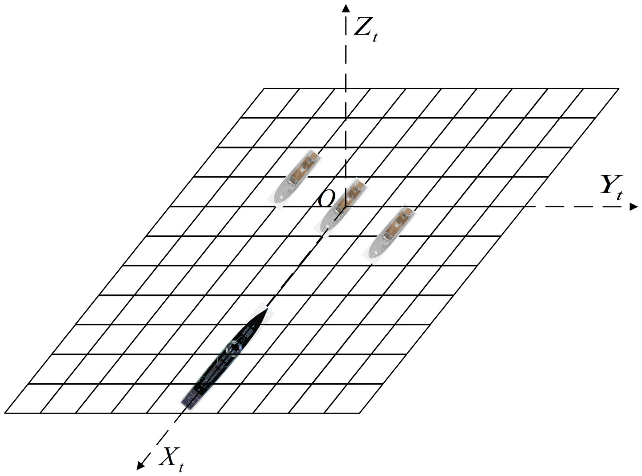


FIGURE 5. Target coordinate system.

[0,1]. (7) illustrates the standard normal distribution of the random numbers.

$$\begin{cases} x = \sqrt{-2\ln\omega_1} \cdot \cos\ (2\pi\omega_2) \\ y = \sqrt{-2\ln\omega_1} \cdot \sin\ (2\pi\omega_2) \end{cases} \tag{7}$$

where x and y represent random numbers conforming to a two-dimensional standard normal distribution, while ω_1 and ω_2 correspond to random numbers uniformly distributed within the interval [0,1]. We hypothesize that actual drop point coordinates follow a two-dimensional normal distribution centered at the aiming point (φ_x, φ_y). Consequently, the bombing point coordinates (B_x, B_y) can be computed by (8).

$$\begin{cases} B_x = \varphi_x + x \cdot CEP/1.774 \\ B_y = \varphi_y + y \cdot CEP/1.774 \end{cases} \tag{8}$$

where CEP denotes the circular error probable of warhead. By using a coordinate conversion method, we transform relative target point coordinates into the ship's target coordinate system. We establish a random ballistic equation by considering the projectile's incoming direction and angle of fall. Upon this ballistic equation, alongside the formation type of USVs and target motion model, we carry out projectile-target rendezvous computations to obtain impact point coordinates, confirm the ammunition's hit position, according to blast point coordinates following the delayed fuse activation law, and establish target destruction probability using the coordinate kill probability model. We performed a statistical analysis of the damage probability of semi-armor-piercing ammunition against USV targets using the Monte Carlo method. A total of S subsamples were selected, and Monte Carlo statistics for each subsample were accumulated to obtain the expected evaluation of subsample damage probability. The Monte Carlo assessment of the average single-shot damage probability for each USV is presented as (9).

$$P_a = \sum_{i=1}^{S} P_i \Big/ S \tag{9}$$

where P_i represents the destruction probability of the ith subsample for each sample. The calculation process is depicted in Fig. 6.

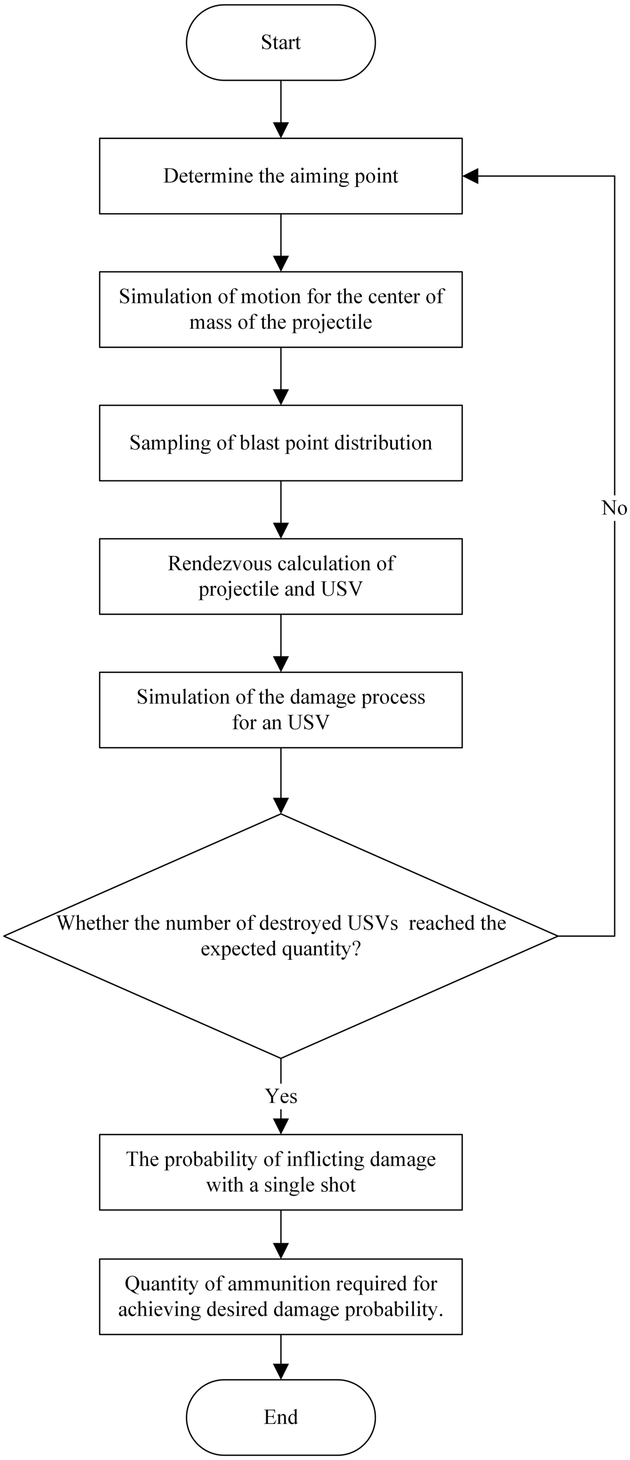


FIGURE 6. Flow chart of the calculation process of the damage effectiveness assessment model.

TABLE 2. Parameters of the virtual test scenario.

Parameters	Values
Destroyer Cruising Speed	30 kn
Speed of the USV	80 kn
Lateral spacing of the USV	200 m
USV Longitudinal spacing	100 m
Distance between USV starting position and Destroyer	20 km
Direction of wind	45°
Speed of wind	2 m/s

TABLE 3. Dimensional parameters of the USV models.

Model	Length(m)	Width(m)	Height(m)
I	3.0m	1.5m	2.0m
II	7.0m	1.9m	2.0m
III	9.0m	2.1m	2.0m
IV	11.0m	3.5m	2.0m

TABLE 4. Parameters for characterising warhead performance.

Parameters	Values
Mean mass of fragmented pieces	3.75 g
Initial velocity of the fragmented pieces	1250 m/s
Orientation angle of fragmented pieces	83°
Dispersion pitch angle of fragmented pieces	42°
TNT equivalence of the unshielded charge	3.5 kg
Circular Error Probable	40 m

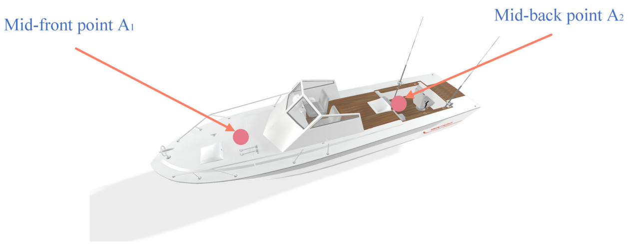


FIGURE 7. The location of aiming point A_1 and A_2.

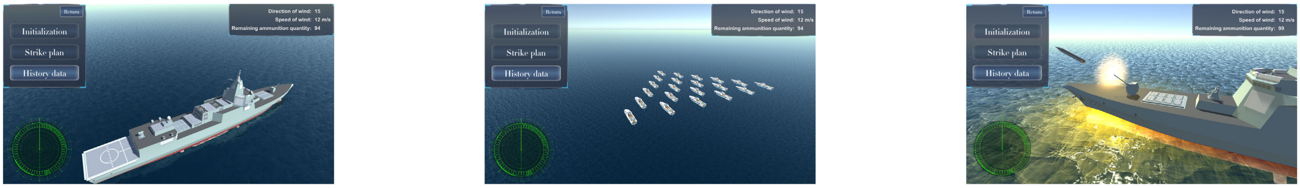
B. DAMAGE EFFECTIVENESS ASSESSMENT EXPERIMENT

We focus on conducting strike tests with large-caliber semi-armor-piercing shells against USV targets, aiming to reduce the preliminary costs of testing new naval weapons and boost their effectiveness in naval warfare. A high-fidelity virtual test scenario is established to statistically evaluate the "single-shot damage probability" and "required ammunition quantity for desired damage probability" under different USV formation combat modes. The parameters of the virtual test scenario are presented in Table 2.

For realistic interactions in the experiments and precise assessments of naval artillery's damage effectiveness on UAVs, we designed three distinct USV models. The dimensional parameters of these models are provided in Table 3.

The process of striking USV targets using naval artillery ammunition within a virtual environment is visualised in Fig. 8.

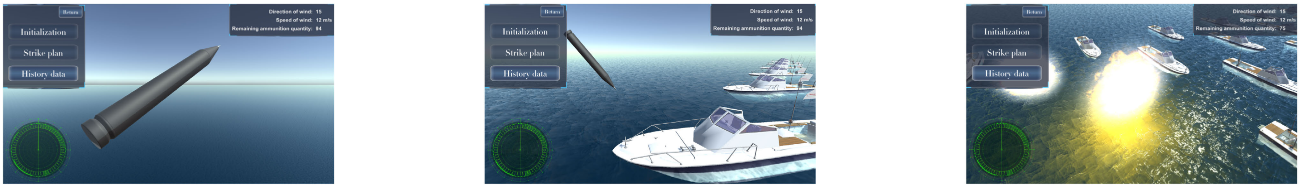
We developed a realistic Unity3D simulation environment for evaluating the effectiveness of semi-armor-piercing rounds against UAVs. This environment facilitates accurate visual and physical interactions, enabling the observation and recording of destruction effects under various parameter



(a) Destroyer on cruise

(b) Random combat formation of USVs

(c) Naval gun Munitions launching



(d) Projectile in flight

(e) Projectile impact approaching point of aim A1

(f) Hits and destroys USV target

FIGURE 8. The process of striking USV targets within a virtual environment.

TABLE 5. Average damage probability statistics for a single projectile.

Groups	USV model	Formation	Damage probability					
			A_1			A_2		
			ANFIS [18]	MNB [15]	Ours	ANFIS [18]	MNB [15]	Ours
1	I	I	0.28	0.33	0.42	0.31	0.38	0.44
2	I	II	0.25	0.3	0.37	0.29	0.37	0.42
3	I	III	0.35	0.42	0.46	0.37	0.43	0.51
4	II	I	0.41	0.47	0.53	0.44	0.51	0.56
5	II	II	0.39	0.45	0.48	0.42	0.49	0.52
6	II	III	0.47	0.53	0.57	0.51	0.55	0.58
7	III	I	0.46	0.54	0.57	0.52	0.56	0.61
8	III	II	0.44	0.52	0.52	0.5	0.53	0.54
9	III	III	0.51	0.57	0.63	0.56	0.59	0.63
10	IV	I	0.56	0.61	0.65	0.57	0.63	0.68
11	IV	II	0.53	0.53	0.58	0.55	0.6	0.62
12	IV	III	0.58	0.63	**0.69**	0.61	0.66	**0.71**

combinations. The performance of the semi-armor-piercing projectile is characterized by specific parameters compiled into a performance dataset. Table 4 presents these warhead performance characterization parameters.

Experiments were conducted on 100 USVs in a simulated environment, taking into account variations in formation and size parameters and working under the hit-is-kill assumption. Each set of experiments was replicated 200 times, to estimate the average probability of damage to USV targets by a single projectile, aimed at points A_1 and A_2 as illustrated in Fig. 7, located at the mid-front and mid-back, respectively.

The damage effectiveness of assessment methods, based on our proposed method, the MNB and the ANFIS, were compared under identical parameters, with the results illustrated in Table 5.

According to the damage probability table, our proposed method outperforms ANFIS and MNB based methods in assessing the damage effectiveness of naval artillery ammunition against USV targets. Although the ANFIS method uses deep learning algorithms for assessing damage effectiveness, it is insufficient to rely solely on four input parameters for accurate calculations related to maritime targets. Relying on a conjugate prior distribution for damage effectiveness determination, the MNB method is sensitive to outliers and anomalies, which makes it less suited for the evaluation of maritime target damage effectiveness. The proposed algorithm for damage assessment, which considers real-time environmental parameters and warhead characterization parameters, accurately computes the trajectory and impact point of a projectile. This feature enhances its reliability in assessing the damage effectiveness of naval artillery ammunition against

TABLE 6. Projectile consumption statistics for assigned task.

Groups	USV model	Formation	Required ammunition quantity					
			A_1			A_2		
			Minimum	Maximum	Average	Minimum	Maximum	Average
1	I	I	29	46	36	27	42	33
2	I	II	33	51	41	30	48	37
3	I	III	24	37	33	22	35	30
4	II	I	25	36	29	25	34	28
5	II	II	27	35	32	25	36	29
6	II	III	22	31	26	21	29	26
7	III	I	24	37	27	21	32	25
8	III	II	23	34	29	21	28	25
9	III	III	21	29	24	17	29	22
10	IV	I	19	31	23	18	27	21
11	IV	II	21	29	26	21	28	25
12	IV	III	**17**	25	21	**16**	23	18

USV targets. We conducted experiments in a virtual scenario on 30 USV targets, each with a 50% expected destruction rate. The aiming points were set at mid-front (A_1) and mid-back (A_2), and the corresponding consumption statistical results are outlined in Table 6.

Comparative analysis according to Table 6 indicates a higher damage probability for USV targets when the aiming point is set at the mid-back point. This is attributed to the relative concentration of the command and control system, detection and fire control system, and electrical system in this area. These findings can serve as a reference for prioritized attack strategies in maritime conflicts. The semi-armor-piercing projectile demonstrated the least ammunition consumption when striking large, densely arranged USV targets with the A2 aiming point. This can be attributed to the substantial fragmentation mass and velocity of the semi-armor-piercing projectile, which results in the warhead posing a greater threat to targets close to the bombing point. Factors such as inherent dispersion, aiming inaccuracies, and meteorological conditions lead to a scatter in the projectile trajectory, causing variations in damage probabilities for ammunition of different precision levels. The relationship between the quantity of ammunition required and the drop angle is illustrated in Fig. 9.

The correlation between ammunition consumption and the drop angle indicates a decrease in ammunition usage as the drop angle increases, with the drop angle having a pronounced effect on ammunition consumption for USV targets. As the CEP decreases, there is a corresponding decline in the quantity of ammunition used at the same drop angle. This decrease can be attributed to improved ammunition accuracy, which in turn increases the probability of successfully destroying a USV target with a single shot. The aforementioned experimental results confirm the alignment of the method for assessing the damage effectiveness of naval artillery against USV targets within the established virtual experimental scenario with real-world conditions. This affirmation validates the stability and versatility of the VR method in assessing the damage effectiveness of naval artillery ammunition against USV targets in combat simulations.

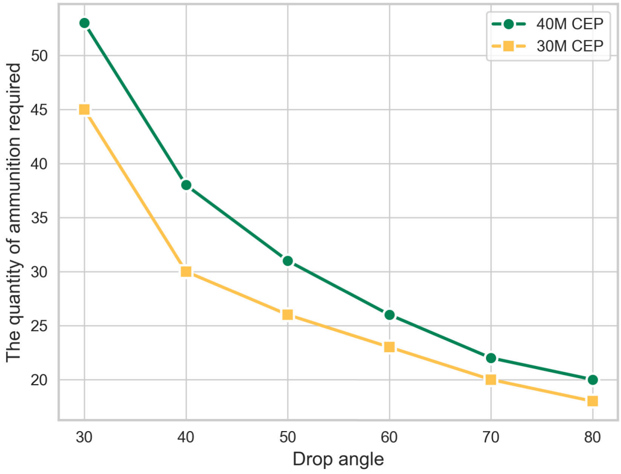


FIGURE 9. The relationship between the quantity of ammunition required and the drop angle.

V. CONCLUSION

The VR technology marks a significant leap forward in evaluating damage effectiveness of destroyers against adversary targets, providing substantial technical aid for simulation based training in maritime exercises and combat scenarios. The VR technology plays an essential role in assuring the accuracy and efficacy of naval artillery ammunition against targets. Presently, damage effectiveness assessment tests for maritime are primarily dependent on actual ship testing. However, this method is not only inefficient and costly but also unable to simulate complex combat environments and fluctuating conditions, thereby falling short of meeting the requirements of maritime combat technology advancement.

As a response, we propose a risk-free, VR guided testing and evaluation methodology for assessing the damage effectiveness of naval artillery ammunition against USV targets. The central technical strategy includes generating virtual test scenario data, using realistic USV formation patterns as references, executing varying complexity levels of attack test tasks, and ultimately deriving damage effectiveness assessment outcomes. On one hand, the application of VR technology and 3D modeling techniques diversifies test scenario designs, enriches test scenario complexity, ensures test task repeatability, and surmounts the limitations of singular scenarios inherent in real ship tests. On the other hand, the selection of evaluation indices that depict the destructive effectiveness of naval artillery ammunition against USV targets, paired with the real-time computation and storage of projectile state information during tests, facilitates a fair and scientifically rigorous evaluation of naval artillery ammunition's destructive capabilities against USV targets. This carries substantial significance for analyzing the performance of naval artillery ammunition and evaluating the reliability and stability of damage effectiveness assessment algorithms.

In future work, we will concentrate on refining the processes of projectile motion and intersection to bolster the accurate simulation of target impacts by naval artillery ammunition. To add the immersiveness of the simulation and help improve the assessment of damage effectiveness, we will optimized the simulation of sound. We also aim to integrate various USV formation modes, strike scenarios, projectile types, and operational contexts, expanding the spectrum of our virtual test scenarios to meet the varying requirements of operational exercise simulations.

REFERENCES

[1] T. Yao, W. Wang, R. Miao, J. Dong, and X. Yan, "Damage effectiveness assessment method for anti-ship missiles based on double hierarchy linguistic term sets and evidence theory," *J. Syst. Eng. Electron.*, vol. 33, no. 2, pp. 393–405, Apr. 2022.

[2] Z. Xu, J. Xue, T. Liu, P. Zhang, and X. Xie, "Equivalent damage study of missile due to energetic fragment warhead," *J. Nanjing Univ. Sci. Technol.*, vol. 44, pp. 348–353, Jun. 2020.

[3] W. Wei, S. Xu, X. He, X. Wang, and T. Yue, "Effectiveness evaluation of air-ground guided ammunition based on combat simulation," *Acta Armamentarii*, vol. 43, no. S1, pp. 107–114, Mar. 2022.

[4] Y. Jing, X. Yang, Y. Liu, and M. Hou, "Evaluation of operational effectiveness for truck-mounted howitzer," *Acta Armamentarii*, vol. 31, no. 6, pp. 787–790, Jun. 2010.

[5] W. Yu and H. Jiang, "Simulation of the damage effectiveness of land-to land missile attacking surface targets," *Acta Armamentarii*, vol. 21, no. 1, pp. 93–95, Feb. 2000.

[6] W. Feng, D. Cui, H. Liu, M. Zhou, H. Li, and Z. Hu, "Influence of warhead parameters of munitions against USV group on combat effectiveness," *Acta Armamentarii*, vol. 43, no. S2, pp. 26–31, Nov. 2022.

[7] J. Tong and P. Wang, "Research on time-on-target firing method of fixed loading ammunition for naval gun," *Proc. SPIE*, vol. 12506, Dec. 2022, Art. no. 1250629.

[8] J. Su, Y. Yao, and W. Wang, "Research on rules of engagement for large-scale unmanned surface vehicle in anti-submarine warfare," in *Proc. Int. Conf. Auton. Unmanned Syst.*, Beijing, China, 2022, pp. 197–206, doi: 10.1007/978-981-16-9492-9_21.

[9] J. Hu, G. Tang, J. Wang, X. Wu, and D. Xie, "Research on unmanned surface vehicle cluster system," *Ship Sci. Technol.*, vol. 41, no. 4, pp. 83–88, Apr. 2019.

[10] R. Dunley, "Uncrewed naval vessels and the span of maritime tasks," *Mar. Policy*, vol. 149, Mar. 2023, Art. no. 105481, doi: 10.1016/j.marpol.2023.105481.

[11] K. Xu, H. Zhang, K. Yan, Y. Zhu, and J. Liu, "The development status and trend of the autonomous ship test area," *Ship Sci. Technol.*, vol. 42, no. 15, pp. 1–6, Aug. 2020.

[12] F. Yang, J. Liu, S. Li, and F. Ma, "Virtual-real interaction tests for functional testing of smart ships," presented at the 30th Int. Ocean Polar Eng. Conf., Paper no. ISOPE-I-20-4265. [Online]. Available: https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE20/All-ISOPE20/446361

[13] J. Xia, Y. Luo, Z. Liu, Y. Zhang, H. Shi, and Z. Liu, "Cooperative multi-target hunting by unmanned surface vehicles based on multi-agent reinforcement learning," *Defence Technol.*, Oct. 2022, doi: 10.1016/j.dt.2022.09.014.

[14] S.-H. Moon, "Weapon effectiveness and the shapes of damage functions," *Defence Technol.*, vol. 17, no. 2, pp. 617–632, Apr. 2021, doi: 10.1016/j.dt.2020.04.009.

[15] H. Liu and X. Shi, "Damage effectiveness calculation of hitting targets with ammunition based on Bayesian multinomial distribution," *Symmetry*, vol. 14, no. 5, Apr. 2022, Art. no. 892, doi: 10.3390/sym14050892.

[16] H. Li, X. Sang, X. Zhang, and K. Yan, "Modeling and analysis of target damage under the multi-posture projectile and target intersection," *IEEE Access*, vol. 7, pp. 135732–135741, 2019, doi: 10.1109/ACCESS.2019.2942694.

[17] H. Li, Y. Hao, and X. Zhang, "Numerical calculation method of target damage effectiveness evaluation under uncertain information of warhead fragments," *Mathematics*, vol. 10, no. 10, May 2022, Art. no. 1688, doi: 10.3390/math10101688.

[18] Z. Wu and Z. Zhao, "A damage assessment model based on adaptive neuro-fuzzy inference system," *Acta Armamentarii*, vol. 33, no. 11, pp. 1352–1357, Nov. 2012. [Online]. Available: http://www.co-journal.com/EN/Y2012/V33/I11/1352

[19] G. Shi, L. Zhang, S. Wang, F. Wu, and Y. Wu, "A kind of high fidelity assessment method for explosive power of anti-ship missile warhead," in *Proc. IEEE 15th Int. Conf. Control Autom. (ICCA)*, Edinburgh, U.K., Jul. 2019, pp. 616–621.

[20] T. Zhu, Y. Wu, M. Zheng, and X. Chu, "Intelligent ship perception test system based on virtual reality interaction," in *Proc. 15th China Intell. Transp. Annu. Conf.*, Shenzhen, China, Nov. 2020, pp. 313–321.

[21] X. Han, H. Liu, and Y. Fan, "Research on testing and evaluation of USV autonomous navigation algorithms based on virtual reality fusion," in *Proc. 41st Chin. Control Conf. (CCC)*, Anhui, China, Jul. 2022, pp. 4329–4336.

[22] F. Lin, L. Ye, V. Duffy, and C. Su, "Developing virtual environments for industrial training," *Inform. Sci.*, vol. 140, nos. 1–2, pp. 153–170, Jan. 2002, doi: 10.1016/S0020-0255(01)00185-2.

[23] S. K. Ong and M. A. Mannan, "Virtual reality simulations and animations in a web-based interactive manufacturing engineering module," *Comput. Educ.*, vol. 43, no. 4, pp. 361–382, Dec. 2004, doi: 10.1016/j.compedu.2003.12.001.

[24] H. Hu and M. Qian, "Research of lntegration system 4CP based on the XML's intermediate platform," *Manuf. Technol. Mach. Tool*, vol. 3, pp. 127–130, Mar. 2010.

[25] S. Yang and S. Fan, "Research progress of virtual testing technology on ship navigation performance," *Ship Eng.*, vol. 33, no. S2, pp. 25–28, Jul. 2011, doi: 10.13788/j.cnki.cbgc.2011.s2.028.

[26] Y. Fan, T. Wang, G. Wang, and H. Liu, "Testing and evaluation of virtual-reality fusion method for unmanned ships formation," in *Proc. 41st Chin. Control Conf. (CCC)*, Anhui, China, Jul. 2022, pp. 5995–6000.

[27] W. Gan, X. Qu, D. Song, H. Sun, T. Guo, and W. Bao, "Research on key technology of unmanned surface vehicle motion simulation based on Unity3D," in *Proc. OCEANS*, Hampton Roads, VA, USA, Oct. 2022, pp. 1–5.

[28] F. Huang, X. Chen, Y. Xu, X. Yang, and Z. Chen, "Immersive virtual simulation system design for the guidance, navigation and control of unmanned surface vehicles," *Ocean Eng.*, vol. 281, Aug. 2023, Art. no. 114884, doi: 10.1016/j.oceaneng.2023.114884.

[29] C. Pan, Z. Peng, L. Liu, and D. Wang, "Data-driven distributed formation control of under-actuated unmanned surface vehicles with collision avoidance via model-based deep reinforcement learning," *Ocean Eng.*, vol. 267, Jan. 2023, Art. no. 113166, doi: 10.1016/j.oceaneng.2022.113166.

[30] J. Rao, X. Xu, H. Bian, J. Chen, Y. Wang, J. Lei, W. Giernacki, and M. Liu, "A modified random network distillation algorithm and its application in USVs naval battle simulation," *Ocean Eng.*, vol. 261, Oct. 2022, Art. no. 112147, doi: 10.1016/j.oceaneng.2022.112147.

[31] M. Song, Q. Shi, Q. Hu, Z. You, and L. Chen, "On the architecture and key technology for digital twin oriented to equipment battle damage test assessment," *Electronics*, vol. 12, no. 1, Dec. 2022, Art. no. 128, doi: 10.3390/electronics12010128.

[32] H. T. Lu, W. B. Li, X. M. Wang, W. B. Li, and C. Chen, "Study on damage ability of anti-armor composite warhead," *Appl. Mech. Mater.*, vols. 494–495, pp. 395–399, Feb. 2014.

[33] S. Wang, X. Han, and X. Wang, "Research on evaluation method of comprehensive power of high explosive warhead and its application," *Acta Armamentarii*, vol. 38, no. 7, pp. 1249–1254, Jul. 2017, doi: 10.3969/j.issn.1000-1093.2017.07.001.

[34] Y. Yang, X. Li, and X. Wang, "An analytical model for propagation and superposition of internal explosion shockwaves in closed cuboid structure," *Acta Armamentarii*, vol. 37, no. 8, pp. 1449–1455, Aug. 2016, doi: 10.3969/j.issn.1000-1093.2016.08.016.

[35] C. Wu and H. Hao, "Modeling of simultaneous ground shock and airblast pressure on nearby structures from surface explosions," *Int. J. Impact Eng.*, vol. 31, no. 6, pp. 699–717, Jul. 2005, doi: 10.1016/j.ijimpeng.2004.03.002.

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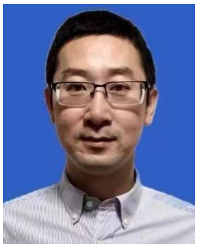

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