Volume 11, Number 1, 2025 69

Simulation of Minefield Installation in a Video Game Engine

Maksym Maksymov[a], Oleksii Neizhpapa[a], Oleksandr Toshev[a,*], Maksym Kiriakidi[b]

[a]*Odesa Polytechnic National University, 1 Shevchenka Ave., Odesa, 65044, Ukraine*
[b]*National University "Odesa Maritime Academy", 8 Didrikhson St., Odesa, 65029, Ukraine*

Received: April 22, 2025. Revised: May 31, 2025. Accepted: June 20, 2025.

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Abstract

In the evolving world of modern digital gaming, particularly within tactical war-game strategies and realistic naval combat environments, the demand for accurate simulation and immersive experience is growing. The design and simulation of naval warfare must integrate more complex systems, including the impact of underwater minefield effectiveness. The research goal is to develop a framework and model that accurately predicts the tactical and operational impact of naval minefields on vessels across diverse gameplay scenarios. The simulation is designed to consider many variables, such as different mine and ship types, different landing strategies, varying environmental parameters and weather. The first objective of this research is to improve damage prediction algorithms, enabling the simulation to more accurately estimate the consequences of ships passing through a minefield. The second objective is to enhance mine allocation logic, developing algorithms that calculate the optimal quantity, type, and distribution of mines needed to halt or delay enemy advances.

Keywords: underwater mines; computer game; simulation framework; game engines; tactical strategy games.

1. Introduction

As computer games continue to evolve, players increasingly seek out highly realistic and deeply immersive experiences. Across various game genres, there is a growing appeal for simulations that let users take control of vehicles, ranging from sports cars to aircraft and naval vessels, and immerse themselves in diverse combat environments.

Within the broader category of simulation games, military-themed titles stand out for their complex modeling of armed forces, equipment, and operational roles. These war-games enable players to step into the shoes of field commanders, operators, or specialized military units, reimagining real-world conflicts or exploring fictional combat scenarios.

In this context, our focus turns to naval strategy, with particular attention to the placement and operational impact of naval minefields installation during sea-based confrontations [1], [2]. Game developers are tasked with building robust simulation frameworks that can realistically portray the mechanics and consequences of mine deployment. This includes the creation of intelligent systems that can determine effective mine-laying patterns, estimate disruption zones for enemy ships, and simulate activation conditions when opposing vessels enter the mine field [3].

Moreover, modeling must account for the logistical and tactical decisions behind minefield planning, including environmental constraints and mission-specific goals. Incorporating these elements not only increases the strategic

[*] Corresponding author. Email address: toshev.oleksandr@outlook.com

This paper should be cited as: M. Maksymov, O. Neizhpapa, O. Toshev, M. Kiriakidi. (2025) Simulation of minefield installation in a video game engine. *Energy Engineering and Control Systems*, Vol. 11, No. 1, pp. 69 – 78. https://doi.org/10.23939/jeecs2025.01.069

depth of gameplay but also helps players make better-informed choices while managing limited defensive resources in dynamic maritime scenarios.

Our game development framework is structured to simulate a broad spectrum of maritime combat scenarios, each presenting unique strategic challenges. The game features a detailed collection of naval mines, categorized by type, functionality, and deployment effectiveness [1], [4]. We also experiment with different deployment strategies to observe how the positioning of minefields affects the flow and outcome of naval engagements. The game further includes a variety of ship classes, each assigned specific roles and operating doctrines. Using our simulation model, we can analyze how different ship formations perform when navigating mined waters under various tactical conditions.

Moreover, the engine integrates detection systems and countermeasure technologies such as mine-hunting vessels and drones, allowing us to assess their performance in neutralizing underwater threats. This comprehensive approach enables precise modeling of the effects of waterborne minefields in multiple combat environments, delivering a highly detailed and engaging simulation of naval defense operations.

Within the framework of strategy-focused video games, players assigned to defend coastal or strategic maritime zones must carefully plan minefield deployment to counter advancing enemy fleets. Success relies on a thorough evaluation of multiple elements, including the opposing force's composition, tactics, and likely paths of approach [5]. Defenders must also assess their own available resources, mine types, and optimal placement zones, while factoring in game environment variables such as sea depth, currents, and weather each of which can affect detection, activation, and navigational hazards.

The primary objective for players managing mine warfare is to create an efficient, sustainable defense strategy that adapts to dynamic threats over time. These simulation-heavy strategy games push players to anticipate enemy maneuvers and respond with calculated precision. The fidelity of the simulation is key to fostering a rich and realistic gameplay experience, promoting strategic innovation and thoughtful decision-making.

In designing a game that accurately portrays naval mine warfare, we draw from real-world military documentation and historical conflict data to set credible baseline parameters for all elements in the simulation. This includes defining activation radius, explosive yield, survivability against clearance operations, and the detection likelihood for each mine type. Similarly, we establish operational characteristics for mine-laying vessels and their limitations. These foundational values ensure that the simulation mirrors real-world operational behavior, providing players with a deep and authentic understanding of tactical engagements shaped by underwater minefields.

2. Analysis of the recent publications and research works on the problem

By analyzing a wide range of scholarly and technical literature on naval mine warfare, we establish a solid foundation for our research. This approach enables us to adopt and refine existing models and methodologies, using them as reference points for developing a robust and effective simulation framework.

The reviewed sources highlight advanced strategies for coordinated deployment of naval minefields, designed to maximize coverage and strategic disruption. One such method emphasizes synchronized mine-laying across multiple zones to ensure that enemy vessels encounter obstacles simultaneously, thereby increasing the likelihood of damage and reducing the chances of successful navigation through the area. These tactics involve precise control over placement timing and spatial distribution, even under variable conditions such as shifting currents or limited communication between mine-laying units. Simulations demonstrate that such coordination significantly improves the effectiveness of minefields in contested environments, especially when considering differing vessel approaches and dynamic sea conditions.

Further literature introduces mathematical models that describe ship behavior when navigating through both safe and mined waters [5], [6]. These models apply an Estimation-Before-Modeling approach, in which key variables, such as ship speed, maneuverability, and hydrodynamic responses are estimated individually before analyzing patterns of vessel movement. The results allow comparison between the maneuvering performance of ships in unaffected conditions versus those affected by mine detonations or near-miss scenarios [7]. These insights provide a deeper understanding of how ships respond under pressure and how damage affects their tactical flexibility.

We use these established studies to define core baseline parameters for our simulation, such as ship attributes, mine trigger mechanisms, explosive yields, and detection probabilities. These parameters allow for a realistic portrayal of tactical interactions within the game environment, from both defensive and offensive standpoints.

Moreover, several works draw upon differential game theory to design optimal strategies for laying minefields in scenarios involving a defender, an intruder, and protected zones. These strategies enable the defender to hinder the attacker's movement while avoiding premature detection or engagement [8], [9]. Notably, these models do not require precise knowledge of the attacker's decisions or path, instead relying on probabilistic patterns and strategic positioning. Simulation results validate the effectiveness of these methods across varying initial conditions and battlefield constraints [4], [10]. Additional research outlines how defenders can preemptively structure minefield networks to reduce the success rate of enemy operations, even in the presence of mine countermeasure technologies.

Drawing on tactical doctrines and strategies outlined in naval warfare literature and operational manuals, we can establish a set of core interactions for our simulation model. These interactions define key gameplay scenarios involving water minefield deployment, segmented into several operational phases:

1) Naval Transit and Amphibious Approach: In this phase, enemy landing fleets transport personnel, vehicles, and equipment toward the target coastline. These vessels are engineered for shore landings under varied sea and weather conditions, often without prior coastal preparation. Ensuring disruption at this stage is critical for delaying or disorganizing the initial wave of the amphibious assault.

2) Deployment of Landing Forces: This stage involves the unloading of troops and materiel from larger transports and landing craft into designated coastal zones or shallow water staging areas. Strategic minefield placement near these drop zones can significantly hinder the safe disembarkation of forces and equipment.

3) Approach Under Fire and Combat Support: As landing vessels move into range of the target shoreline, they provide covering fire to neutralize defensive assets and secure landing zones. Minefields, especially influence or intelligent variants, placed near fire support routes or expected anchor positions can limit maneuverability and disrupt coordination.

4) Sustainment and Extraction Operations: Landing forces rely on logistical support from the sea to maintain combat effectiveness, including the delivery of ammunition, supplies, and medical evacuation. Mines placed along supply lanes or extraction routes serve to constrain movement and impose long-term pressure on sustained enemy operations.

The defending player has strategic freedom to initiate mine-laying operations or rely on pre-deployed fields during any of these phases. Timing is critical, decisions must weigh resource availability, real-time battlefield intelligence, environmental conditions, and enemy fleet behavior. Choosing the most impactful moment to activate or reinforce minefields can be decisive in preventing a successful enemy landing and turning the tide of the operation.

3. Objectives and tasks of the research

The core gameplay scenario is structured around two opposing players. The first, acting as the attacker, is tasked with escorting a squadron of landing ships to enemy-controlled waters to initiate an amphibious landing. The attacking force is composed of landing vessels, protective escort ships and minesweeper ships. The defending player, on the other hand, primarily relies on naval mines and supporting detection and disruption systems to halt the enemy advance.

The main objective for the defending player is to deploy and manage underwater minefields in a way that maximizes damage to the incoming landing fleet and effectively disrupts or halts the amphibious operation. This requires high levels of operational readiness, where mine-laying vessels, surveillance units, and crew are well-prepared and positioned strategically to execute their mission with precision and speed.

The initial focus of the research is to develop and refine a simulation model that can estimate the potential impact of minefield deployment on invading landing ships, taking into account all relevant factors including mine type, density, placement pattern, and detection probability.

The second goal is to establish a method for calculating the optimal number and configuration of mines required to successfully block or degrade a landing operation. This would provide valuable decision-making tools for both players and AI systems, enhancing their ability to make strategic choices under varying conditions and mission parameters within the game environment.

4. Model and methods

The simulation model centers on the strategic task of employing underwater minefields to disrupt and neutralize enemy landing operations, with an emphasis on identifying optimal deployment tactics for common gameplay scenarios.

The arrangement of the defending player's forces is fine-tuned to meet mission-specific objectives, guided by criteria that define effective minefield utilization. To configure these forces properly, the player must assess the operational capabilities of mine-laying vessels, available mine types, and the prevailing tactical context. This includes calculating the ideal density and layout of mine placements, grouping mine-laying units for coordinated deployment, and determining the sequencing and timing of their actions.

The positioning and use of minefield zones are also influenced by the attacking player's escort fleet configuration, as its defensive strength directly affects the survivability of incoming landing vessels. Exploring different configurations of defensive forces, such as varying the number, type, or quality of mines and deployment platforms is vital for understanding how these variables shape the overall success of the mission. In the base scenario, an increase in the number or complexity of escort ships in the attacking player's formation requires a corresponding escalation in the scale and sophistication of minefield defenses.

Determining the appropriate quantity and type of deployed mines, along with the necessary support infrastructure, involves detailed tactical analysis. To aid players in making informed decisions, these findings must be presented in a way that clearly demonstrates how minefield effectiveness shifts under different operational conditions. This process requires comprehensive modeling, scenario-based comparisons, and conclusions that highlight the advantages and limitations of each potential setup.

Once the player receives a mission directive, they can draw on prior calculations to choose a suitable configuration or refine their strategy in response to evolving in-game factors.

To make an estimate for an effectiveness of a minefield we need to calculate multiple values, such as:

- The expected number of destroyed ships when passing through a minefield consisting of a certain number of mines.

- The expected number of mines requires to form a minefield to destroy a certain number of ships which are passing through.

- The expected combat resistance of the minefield against various mine countermeasures.

To calculate mathematical expectation for the number of destroyed ships from a group of *N* ships, we can use a formula:

$$M_N = m\frac{A}{A_p}RS\alpha, \tag{1}$$

where m is a number of columns in the convoy; A is a mine hit area; A_p is a mine response area on a ship; R is a minefield density; S is an area of mine barrier, based on a fairway; α is a relative part of an S area affected by passing ships.

The area of a mine barrier S could be calculated using the following formula:

$$S = A + l_s E_k, \tag{2}$$

where E_k is a mean deviation of the ship's position dispersion relative to the general course of the column; l_s is a stochastic coefficient which depends on environment conditions.

α value is a statistical coefficient which depends on a number of columns in the convoy, number of ships in each column and an area which convoy covers.

The average deviation of the ship's position dispersion relative to the general course of the column E_k could be calculated by the formula:

$$E_k = \sqrt{(rD_k)^2 + V_k^2}, \tag{3}$$

where D_k is a distance between ships in a convoy; V_k is an estimated speed of a convoy.

Minefield density R could be calculated by the following formula:

$$R = \frac{M_N}{m\frac{A}{A_p}S\alpha}K_i, \tag{4}$$

where M_N is a required mathematical expectation of a number of destroyed ships from a total number of N ships in a convoy; K_i is a statistical coefficient which defines effectiveness of used mines and mine installing equipment.

The number of required mines to build an effective minefield N could be calculated by the formula:

$$N = \frac{RA}{K_i}. \tag{5}$$

To enable mine ships to deploy the required number of naval mines, it is important to calculate the mine placement interval. Different type mines have varying effective trigger ranges. The interval must ensure that adjacent mines' activation zones either overlap or leave minimal gaps to avoid safe passages. The mine placing ships velocity during deployment determines the time between drops. For example, at higher speeds, a shorter time interval is needed to maintain a consistent spacing.

To calculate an interval, we can use the below formula:

$$I = \frac{A}{N}. \tag{6}$$

To evaluate the combat resistance of a minefield, we will define it as the amount of time it takes for opposing mine countermeasure forces to breach the minefield and establish a navigable, safe corridor for the convoy. This measurement will account for the complexity and density of the mine distribution, the types of naval mines used (contact, influence, or smart mines), and their spatial layout across the waterway.

The total clearance time required to establish a secure passage through the minefield will serve as a quantitative metric of its combat resistance. A longer clearance time indicates higher resistance and greater effectiveness in delaying or disrupting enemy maritime operations.

As an example for our model, we will make calculations for one of the basic types for naval mines countermeasures – naval minesweeper with a mine-clearing line charge.

To calculate number of required mine-clearing line charges N_c we can use the following formula:

$$N_c = \frac{W_f}{M\sigma} * \frac{L_f}{l\sigma}, \tag{7}$$

where W_f and L_f are width and length of a fairway required for the safe passage of a convoy; M is a width of a line cleared of mines when cord charges explode; σ is a statistical error for setting up a line charge before exploding; l is a length of a mine-clearing line charge.

Time t_c required for minesweepers for traveling and setting up line charges could be calculated by the following formula:

$$t_c = t_t + \frac{2L}{V} + t_s, \tag{8}$$

where t_t is a time needed for arming minesweepers with a required number of charges; t_s is a time required to setup all mine-clearing line charges; L is a distance to the fairway from a doc station of a minesweepers; V is a speed of a minesweepers.

The time T_s needed for destroying mines by a mine-clearing line charges is calculated using the formula:

$$T_s = N_c t_c, \tag{9}$$

where N_c is a number of a setups of a line charges, required to clear a fairway of a certain size; t_c is a time required for a minesweepers for preparations, traveling, setting up and exploding required amount of a line charges.

The range of combat stability of a minefield T_r is the range of the total time T of completing the task, which is calculated from a working time required to working days according to the formula and rounded to a whole number in the higher direction:

$$T_r = T_s\tau + (\frac{T_s\tau}{n_a} - 1)t_r, \quad (10)$$

where τ is a statistical coefficient which depends on an outside factors, such as weather; n_a is a time during which a minesweeper could operate without an additional service, depends on a type of a minesweeper; t_r is a time required for a full service of a minesweeper, also depends on a type of a minesweeper ship.

5. Experiments

Experiment 1. Determine the number of mines required to install naval minefield against enemy landing convoy. Enemy convoys consist of 60 ships. To effectively stop enemy landing operation, it is required to destroy at least 12 ships and ensure combat resistance of a minefield more than 96 hours. Possible passing area is 15 miles wide and 5 miles long. It is expected for ships to be divided into 5 columns. The distance between ships is 0.4 miles. Speed of ships in convoy 12 knots.

In the experiment, we are using mines of "M1" type which have 35m hit radius and 40m response radius.

Opposing convoys is supported by 4 minesweepers of type "MS1".

For the ships which are placing mines we will define coefficient: $K_i = 0.95$.

For a mines of type "M1": $A = 35,\ A_p = 40$.

Columns in a convoy: $m = 5$.

Statistical coefficient: $r = 6.25$.

Using formula (3) we can calculate the average deviation of the ship's position dispersion relative to the general course of the column:

$$E_k = \sqrt{(6.25 * 0.4)^2 + 12^2} = 29.816.$$

Statistical coefficient which depends on a number of columns in the convoy, number of ships in each column and an area which convoy covers: $\alpha = 0.488$.

The statistical coefficient for the environment: $l_s = 10$.

The area of a mine barrier we can calculate with formula (2):

$$S = 35 + 10 * 29.816 = 333.$$

We can calculate minefield density with the formula (4):

$$R = \frac{12}{5 * \frac{35}{40} * 333 * 0.488} * 0.95 = 0.01685.$$

Using formula (5) we can calculate the number of required mines to build an effective minefield:

$$N = \frac{0.01685 * 15 * 1852}{0.95} = 492.$$

With a calculated required number of mines, we can calculate an interval at which mines should be placed with the below formula (6):

$$I = \frac{15*1852}{492} \approx 56.5.$$

Using the same formula, we can make different calculations for the same environment setup and enemy forces, for different mine placing intervals and variable number of columns in a convoy to get the mathematical expectation for a number of destroyed ships (Fig.1).

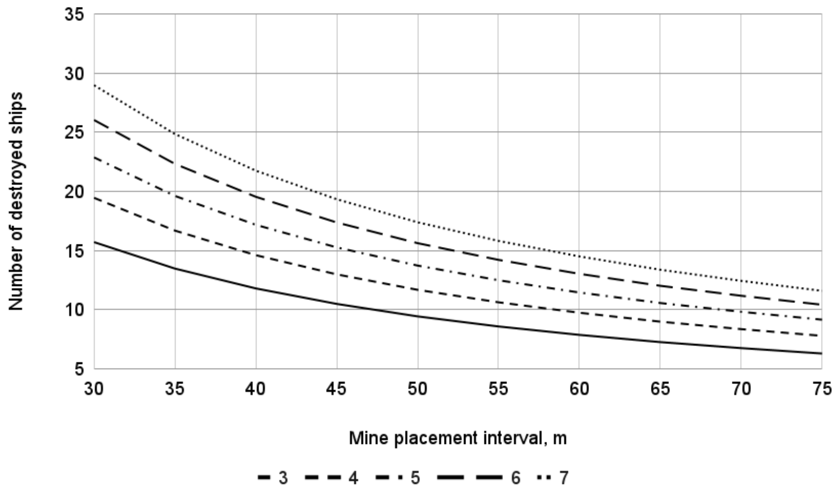

Fig.1. Estimated number of destroyed ships for a set interval for mines placement for experiment 1.

The results of our calculations provide a better understanding of how different minefield configurations affect the outcome of enemy landing operations. This information enables us to make highly optimized strategic decisions that balance maximum defensive effectiveness with efficient resource utilization.

For the chosen type of minesweeper and supporting equipment, we can define required variables, such as width of a line cleared of mines when cord charges explode $M = 185$, and the length of a mine-clearing line charge $l = 1000$.

Number of required mine-clearing line charges could be calculated with the formula (7):

$$N_c = \frac{15*1852}{185\sigma} * \frac{5*1852}{1000\sigma} = 48.$$

Time needed for arming minesweepers with a required number of charges $t_t = 1$, time required to setup all mine-clearing line charges $t_s = 1$, distance to the fairway from a doc station of a minesweepers $L = 15$, speed of a minesweepers $V = 10$.

To calculate (8) time t_c required for minesweepers for traveling and setting up line charges:

$$t_c = 1 + \frac{2*15}{10} + 1 = 5.$$

The time T_s needed for destroying mines by a mine-clearing line charges we can calculate with the formula (9):

$$T_s = \frac{48*5}{12} = 20.$$

For the chosen types of minesweepers: time during which a minesweeper could operate without an additional service $n_a = 5$, t_r is a time required for a full service of a minesweeper $t_r = 2$, and statistical coefficient which is $\tau = 1.43$.

The range of combat stability of a minefield we can calculate with the formula (10):

$$T_r = 20 * 1.43 + \left(\frac{20*1.43}{5} - 1\right) * 2 = 5 * 24h = 120h.$$

Experiment 2. For the second experiment, let's define the setup with smaller landing forces and smaller area of possible passage. Enemy convoys consist of 12 ships. To effectively stop enemy landing operation, it is required to destroy at least 4 ships and ensure combat resistance of a minefield more than 48 hours. Possible passing area is 4 miles wide and 2 miles long. It is expected for ships to be divided into 3 columns. The distance between ships is 0.5 miles. Speed of ships in convoy is 14 knots.

For this experiment, we will use the same types of mines, ships and minesweepers.

$K_i = 0.95, A = 35,\ A_p = 40.$

Columns in a convoy: $m = 3$.

Statistical coefficient: $r = 6.25$.

Using formula (3), we can calculate the average deviation of the ship's position dispersion relative to the general course of the column:

$$E_k = \sqrt{(6.25 * 0.5)^2 + 14^2} = 35.84.$$

Statistical coefficient $\alpha = 0.314$.

The statistical coefficient for the environment: $l_s = 10$.

The area of a mine barrier we can calculate with formula (2):

$$S = 40 + 10 * 35.84 = 393.4.$$

We can calculate minefield density with the formula (4):

$$R = \frac{4}{3 * \frac{35}{40} * 393 * 0.314} * 0.95 = 0.0123.$$

We can calculate the number of required mines to build an effective minefield:

$$N = \frac{0.0123 * \ 4 * 1852}{0.95} = 96.$$

With a calculated required number of mines we can calculate an interval at which mines should be placed using the below formula (6):

$$I = \frac{4*1852}{96} \approx 77.$$

Let's make the same calculations for the same environment setup and enemy forces, for different mine placing intervals and variable number of columns in a convoy (Fig.2).

Let's calculate the number of required mine-clearing line charges with the formula (7):

$$N_c = \frac{4*1852}{185\sigma} * \frac{2*1852}{1000\sigma} = \ 24.$$

With the same setup for the minesweepers we got variables $t_t = 1,\ t_s = 1, L = 15, V = 10$.

$$t_c = 3.5.$$

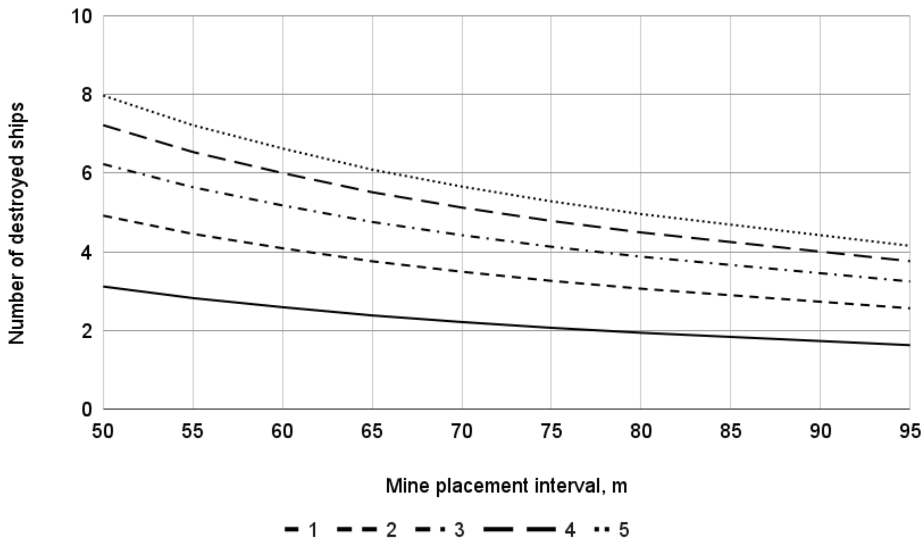

Fig.2. Estimated number of destroyed ships for a set interval for mines placement for experiment 2.

The time T_s needed for destroying mines by a mine-clearing line charges:

$$T_s = 7.$$

For the chosen types of minesweepers: $n_a = 5$, $t_r = 2$, $\tau = 1.43$.

The range of combat stability of a minefield:

$$T_r = 3 * 24h = 72h.$$

6. Conclusion

A simulation model has been developed to assess the effectiveness of naval minefields in countering naval landing operations. This model incorporates all critical components typically involved in such operations, including landing vessels transporting troops and equipment, escort and supply ships of various classes, and different tactical compositions of the opposing player's naval task force.

The model identifies the optimal density and configuration of minefields necessary to fulfill the objective of halting the adversary's landing attempt by neutralizing or obstructing elements of their amphibious group. It enables the selection and evaluation of multiple defensive configurations, helping players determine the most effective layout based on the specific tactical situation in the game scenario.

Experimental simulations validate the model's versatility, demonstrating its application across a wide range of enemy fleet configurations. By comparing outcomes for different setups of the attacking player's naval group, including variations in ship classes, support elements, the model provides insights into the contribution of each component to the success or failure of a landing attempt.

This modeling tool empowers both human players and game AI to rapidly devise and implement effective mine warfare strategies. It enables accurate scenario forecasting and supports critical planning decisions such as minefield size, deployment timing, type of mines to be used, and placement zones, all aimed at preventing or severely disrupting the rival player's naval landing operation.

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Симуляція встановлення мінного поля у відеоігровому рушієві

Максим Максимов[a], Олексій Неїжпапа[a], Олександр Тошев[a], Максим Кіріакіді[b]

[a]Національний університет «Одеська політехніка», Пр. Шевченка, 1, 65044, м. Одеса, Україна
[b]Національний університет «Одеська морська академія», вул. Дідріхсона, 8, 65029, м. Одеса, Україна

Анотація

У світі сучасних цифрових ігор, особливо в рамках тактичних військових стратегій та реалістичних морських бойових середовищ, зростає попит на точне моделювання та захопливий досвід. Проектування та моделювання морських бойових дій повинні інтегрувати складніші системи, та включно вплив ефективності підводних мінних полів. Метою цього дослідження є розробка алгоритму та моделі, яка точно прогнозує тактичний та оперативний вплив морських мінних полів на судна в різних ігрових сценаріях. Моделювання розроблено з урахуванням багатьох змінних, таких як різні типи мін та кораблів, різні стратегії висадки, різні параметри навколишнього середовища та погоди. Першою метою цього дослідження є вдосконалення алгоритмів прогнозування пошкоджень, що дозволить моделюванню точніше оцінювати наслідки проходження кораблів через мінне поле. Другою метою є вдосконалення логіки розподілу мін, розробка алгоритмів, які розраховують оптимальну кількість, тип та розподіл мін, необхідних для зупинки або затримки просування противника.

Ключові слова: підводні міни; комп’ютерна гра; структурне моделювання; ігрові двигуни; тактичні стратегічні ігри.